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**THE MATHEMATICAL THEORY OF  
PROBABILITIES**



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# THE MATHEMATICAL THEORY OF PROBABILITIES

AND  
ITS APPLICATION TO FREQUENCY CURVES AND  
STATISTICAL METHODS

BY  
ARNE FISHER, F.S.S.  
(LONDON)

TRANSLATED AND EDITED  
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WITH THE ASSISTANCE

OF  
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(BELFAST)

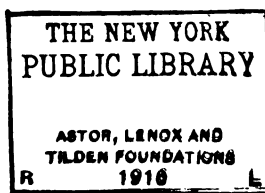
WITH AN INTRODUCTORY NOTE

BY  
F. W. FRANKLAND, F.I.A., F.A.S., F.S.S.  
EXAMINER IN STATISTICAL METHOD AND IN PURE MATHEMATICS TO THE  
GOVERNMENT OF NEW ZEALAND

VOLUME I.  
MATHEMATICAL PROBABILITIES AND HOMOGRAPHIC  
STATISTICS

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AS A TOKEN OF ESTEEM FOR THE GREAT INTEREST WHICH HE, SO  
MARKEDLY AMONG THE DISTINGUISHED LIFE INSURANCE EXEC-  
UTIVES OF AMERICA, HAS ALWAYS SHOWN IN WHATEVER  
HAS TENDED TO PROMOTE THE STUDY AND DEVELOP-  
MENT OF ACTUARIAL AND STATISTICAL SCIENCE



## INTRODUCTORY NOTE.

I feel it a great honor to have been asked by my friend and colleague, Mr. Arne Fisher, of the Equitable Life Assurance Society of the United States, to write an introductory note to what appears to me the finest book as yet compiled in the English language on the subject of which it treats. As an Examiner myself in Statistical Method for a British Colonial Government, it has been to me a heart-breaking experience, when implored by intending candidates for examination to recommend a text-book dealing with Mr. Fisher's subject matter, that it has heretofore been impossible for me to recommend one in the English language which covers the whole of the ground. Until comparatively recent years the case was even worse. While in French, in Italian, in German, in Danish, and in Dutch, scientific works on statistics were available galore, the dearth of such literature in the English language was little short of a national or racial scandal. With such works as those of Yule and Bowley, in recent years, there has been some possibility for the English-speaking student to acquire part of the knowledge needed. But it is hardly necessary to point out what a very large amount of new ground is covered by Mr. Fisher's new book as compared with such works as I have referred to.

Despite my professional connection with statistical and actuarial work of a technical character my own personal interest in Mr. Fisher's book is concentrated principally on the metaphysical basis of the Probability-theory, and it is with regard to this aspect of the subject alone that I feel qualified to comment on his achievement. With all the controversy that has gone on through many decades among metaphysicians and among writers on logic interested especially in the bases of the theories of probability and induction, between the pure empiricists of the type of J. S. Mill and John Venn (at all events in the earliest edition of his work) on the one hand, and the (partly) *à priori* theorists who base their doctrine on the foundation of Laplace on the other hand, it has

been a source of intense satisfaction to me, as in the main a disciple of the latter group of theorists, to note the masterly way in which Mr. Arne Fisher disentangles the issues which arise in the keen and sometimes almost embittered controversy between these two schools of thought. It has always seemed to the present writer as if the very foundations of Epistemology were involved in this controversy. The impossibility of deriving the corpus of human knowledge exclusively from empirical data by any logically valid process—an impossibility which led Immanuel Kant to the creation of his epoch-making philosophical system—is hardly anywhere made more evident than in what seems to the present writer the unsuccessful effort of thinkers like John Venn to derive from such purely empirical data the entire Theory of Probability. The logical fallacy of the process is analogous to that perpetrated by John Stuart Mill in endeavoring to base the Law of Causality on what he termed an "*inductio per simplicem enumerationem*." Probably there is nowhere a more trenchant and conclusive exposure of the unsoundness of this point of view, than in the Right Honorable Arthur James Balfour's monumental work "A Defense of Philosophic Doubt." It is therefore satisfactory to find that Mr. Fisher emphasizes, quite at the beginning of his treatise, that an *à priori* foundation for "Probability" judgments is indispensable.

Hardly less gratifying, from the metaphysical point of view, is Mr. Fisher's treatment of the celebrated *quaestio vexata* of Inverse Probabilities and his qualified vindication of Bayes' Rule against its modern detractors.

Aside altogether from metaphysics, it is particularly satisfactory to note the full and clear way in which the author treats the Lexian Theory of Dispersion and of the "Stability" of statistical series and the extension of this theory by recent Scandinavian and Russian investigators,—a branch of the science which has till the appearance of this new work not been adequately covered in English text-books.

It may of course be a moot question whether the preference given by our author to Charlier's method of treating "Frequency Curves" over the method of Professor Karl Pearson is well advised. But whatever the experts' verdict may be on debatable

questions like these, the scientific world is to be congratulated on Mr. Fisher's presentment of a new and sound point of view, and he emphatically is to be congratulated on the production of a text-book which for many years to come will be invaluable both to students and to his confrères who are engaged in extending the boundaries of this fascinating science.

F. W. FRANKLAND,

*Member of the Actuarial Society of America,  
Fellow of the Institute of Actuaries of Great  
Britain and Ireland, and Fellow of the  
Royal Statistical Society of London.*

NEW YORK,  
October 1, 1915.



## PREFACE.

"Probability" has long ago ceased to be a mere theory of games of chance and is everywhere, especially on the continent, regarded as one of the most important branches of applied mathematics. This is proven by the increasing number of standard text-books in French, German, Italian, Scandinavian and Russian which have appeared during the last ten years. During this time the research work in the theory of probabilities has received a new impetus through the labors of the English biometricians under the leadership of Pearson, the Scandinavian statisticians Westergaard, Charlier and Kiær, the German statistical school under Lexis, and the brilliant investigations of the Russian school of statisticians.

Each group of these investigations seems, however, to have moved along its own particular lines. The English schools have mostly limited their investigations to the field of biology as published in the extensive memoirs in the highly specialized journal, *Biometrika*. The Scandinavian scholars have produced researches of a more general character, but most of these researches are unfortunately contained in Scandinavian scientific journals and are for this reason out of reach to the great majority of readers who are not familiar with any of the allied Scandinavian languages. This applies in a still greater degree to the Russians. German scholars of the Lexis school have also contributed important memoirs, but strangely enough their researches are little known in this country or in England, a fact which is emphasized through the belated English discussion on the theory of dispersion as developed by Lexis and his disciples. The same can also be said with regard to the Italian statisticians.

In the present work I have attempted to treat all these modern researches from a common point of view, based upon the mathematical principles as contained in the immortal work of the great Laplace, "Théorie analytique des Probabilités," a work which despite its age remains the most important contribution to the

theory of probabilities to our present day. Charlier has rightly observed that the modern statistical methods may be based upon a few condensed rules contained in the great work of Laplace. This holds true despite the fact that many modern English writers of late have shown a certain distrust, not to say actual hostility, towards the so-called mathematical probabilities as defined by the French savant, and have in their place adopted the purely empirical probability ratios as defined by Mill, Venn and Chrystal. It is quite true that it is possible to build a consistent theory of such ratios, as for an instance is done by the Danish astronomer and actuary, Thiele. The theory, however, then becomes purely a theory of observations in which the theory of probability takes a secondary place. The distrust in the so-called mathematical a priori probabilities of Laplace I believe, however, to be unfounded, and the criticism to which that particular kind of probabilities is subjected by a few of the modern English writers is, I believe, due to a misapprehension of the true nature of the Bernoullian Theorem. This renowned theorem remains to-day the cornerstone of the theory of statistics, and upon it I have based the most important chapters of the present work. Following the beautiful investigations of Tscheycheff and Pizetti in their proofs of Bernoulli's Theorem and the closely related theorem of large numbers by Poisson I have adopted the methods of the Swedish astronomer and statistician, Charlier, in the discussion of the Lexian dispersion theory.

The theory of frequency curves is treated from various points of view. I have first given a short historical introduction to the various investigations of the law of errors. The Gaussian normal curve of error was by the older school of statisticians held to be sufficient to represent all statistical frequencies, and actual observed deviations from the normal curve were attributed to the limited number of observations. Through the original memoirs of Lexis and the investigations of Thiele the fallacy of such a dogmatic belief was finally shown. The researches of Thiele, and later of Pearson, developed later the theory of skew curves of error. As recently as 1905 Charlier finally showed that the whole theory of errors or frequency curves may be brought back to the principles of Laplace. I have treated this

subject by the methods of both Pearson and Charlier, although I have given the methods of the latter a predominant place, because of their easy and simple application in the practical computations required by statistical work. The mathematical theory of correlation, which is treated in an elementary manner only, is based upon the same principles.

The statistical examples serve as illustrations of the theory, and it will be noted that it is possible to solve all the important statistical problems presenting themselves in daily work on the basis of a theory of mathematical probabilities instead of on a direct theory of statistical methods. I have here again followed Charlier in dividing all statistical problems into two distinct groups, namely, the homograde and the heterograde groups.

In treating the philosophical side of the subject I have naturally not gone into much detail. However, I have tried to emphasize the two diametrically opposite standpoints, namely the principle of what von Kries has called the principle of "cogent reason," and the principle which Boole has aptly termed "the equal distribution of ignorance." These two principles are clearly illustrated in the case of the so-called inverse probabilities. As far as pure theory is concerned, the theory of "inverse probabilities" is rigorous enough. It is only when making practical applications of the rule of inverse probabilities (the so-called Bayes' Rule) that many writers have made a fatal mistake by tacitly assuming the principle of "insufficient reason" as the only true rule of computation. This leads to paradoxical results as illustrated by the practical problem from the region of actuarial science in Chapter VI in this book.

In a work of this character I have naturally made an extended use of the higher mathematical analysis. However, the reader who is not versed in these higher methods need not feel alarmed on this account, as the elementary chapters are arranged in such a way that the more difficult paragraphs may be left out. I have in fact divided the treatise into two separate parts. The first part embraces the mathematical probabilities proper and their applications to homograde statistical series. This part, I think, constitutes what is usually given as a course in vital statistics in many American colleges. I hardly deem it worth while to give a

detailed discussion on the collection and arrangement of the statistical data as to various frequency distributions. The mere graphical and serial representation of frequency functions by means of histograms and frequency columns is so simple and evident that a detailed description seems superfluous. The fitting of the various curves to analytical formulas and the determination of the various parameters seem to me of much greater importance. The theory of curve fitting which is treated in the second volume is founded upon a more advanced mathematical analysis and is for this reason out of reach to the average American student who desires to learn only the rudiments of modern statistical methods. Practical statisticians, on the other hand, will derive much benefit from these higher methods. It is a fact generally noted in mathematics that the practical application of a difficult theory is much simpler than that of a more elementary theory. This is amply proven by the appearance of an excellent little Scandinavian brochure by Charlier: "*Grunddragen af den matematiske Statistikken*." ("Rudiments of Mathematical Statistics.") I have always attempted to adapt theory to actual practical problems and requirements rather than to give a purely mathematical abstract discussion. In fact it has been my aim to present a theory of probabilities as developed in recent years which would prove of value to the practical statistician, the actuary, the biologist, the engineer and the medical man, as well as to the student who studies mathematics for the sake of mathematics alone.

The nucleus of this work consisted of a number of notes written in Danish on various aspects of the theory of probabilities, collected from a great number of mathematical, philosophical and economic writings in various languages. At the suggestion of my former esteemed chief, Mr. H. W. Robertson, F.A.S., Assistant Actuary of the Equitable Life Assurance Society of the United States, I was encouraged to collect these fragmentary notes in systematic form. The rendering in English was done by myself personally with the assistance of Mr. W. Bonyngé. With his assistance most of the idiomatic errors due to my barbaric Dano-English have been eliminated. The notes stand, however, in the main as a faithful reproduction of my original

English copy. Although the resulting "Dano-English" may have its great shortcomings as to rhetoric and grammar, I hope to have succeeded in expressing what I wanted to say in such a manner that my possible readers may follow me without difficulty.

I gladly take the opportunity of expressing my thanks to a number of friends and colleagues who in various ways have assisted me in the preparation of this work. My most grateful thanks are due to Mr. F. W. Frankland, Mr. H. W. Robertson and Mr. Wm. Bonyngne not only for reading the manuscript and most of the proofs, but also for the friendly help and encouragement in the completion of this volume. The introductory note by Mr. Frankland, coming from the pen of a scholar who for the most of a life-time has worked with statistical-mathematical subjects and who has taken a special interest in the philosophical and metaphysical aspects of the probability theory, I regard as one of the strong points of the book. My debts to Messrs. Frankland and Robertson as well as to Dr. W. Strong, Associate Actuary of the Mutual Life Insurance Company, are indeed of such a nature that they cannot be expressed in a formal preface. My thanks are also due to Mr. A. Pettigrew in correcting the first rough draught of the first three chapters at a time when my knowledge of English was most rudimentary, to Mr. M. Dawson, Consulting Actuary, and Mr. R. Henderson, Actuary of the Equitable Life, for reading a few chapters in manuscript and making certain critical suggestions, to Professors C. Grove and W. Fite, of Columbia University, for numerous technical hints in the working out of various mathematical formulas in Chapter VI, to Miss G. Morse, librarian of the Equitable Library, in the search of certain bibliographical material. Last but not least I wish to express my sincerest thanks to several of my Scandinavian compatriots for allowing me to quote and use their researches on various statistical subjects. I want in this connection especially to mention Professor Charlier, of Lund, and Professors Westergaard and Johannsen, of Copenhagen.

To The Macmillan Company and The New Era Printing Company I beg leave to convey my sincere appreciation of their very courteous and accommodating attitude in the manufacture of

this work. Their spirit has been far from commercial in this—  
from a pure business standpoint—somewhat doubtful under-  
taking.

ARNE FISHER.

NEW YORK,  
October, 1915.

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## CHAPTER I.

### INTRODUCTION: GENERAL PRINCIPLES AND PHILOSOPHICAL ASPECTS.

**1. Methods of Attack.**—The subject of the theory of probabilities may be attacked in two different ways, namely in a philosophical, and in a mathematical manner. At first the subject originated as isolated mathematical problems from games of chance. The pioneer writers on probability such as Cardano, Galileo, Pascal, Fermat, and Huyghens treated it in this way. The famous Bernoulli was, perhaps, the first to view the subject from the philosopher's point of view. Laplace wrote his well-known "*Essai Philosophique des Probabilités*," wherein he terms the whole science of probability as the application of common sense. During the last thirty years numerous eminent philosophical scholars such as Mill, Venn, and Keynes of England, Bertrand and Poincaré of France, Sigwart, von Kries and Lange of Germany, Kroman of Denmark, and several Russian scholars have written on the philosophical aspect.

In the ordinary presentation of the elements of the theory of probability as found in most English text-books, the treatment is wholly mathematical. The student is given the definition of a mathematical probability and the elementary theorems are then proved. We shall, in the following chapter, depart from this rule and first view the subject, briefly, from a philosophical standpoint. What the student may thus lose in time we hope he may gain in obtaining a broader view of the fundamental principles underlying our science. At the same time, the reader who is unacquainted with the science of philosophy or pure logic, need not feel alarmed, since not even the most elementary knowledge of the principles of formal logic is required for the understanding of the following chapter.

**2. Law of Causality.**—In a great treatise on the Chinese civilization, Oscar Peschel, the German geographer and philosopher, makes the following remarks: "Since our intellectual awakening, since we have appeared on the arena of history as the creators

and guardians of the treasures of culture, we have sought after only one thing, of the presence of which the Chinese had no idea, and for which they would give hardly a bowl of rice. This invisible thing we call causality. We have admired a vast number of Chinese inventions, but even if we seek through their huge treasures of philosophical writing we are not indebted to them for a single theory or a single glance into the relation between cause and effect."

The law of causality may be stated broadly as follows: Everything that happens, and everything that exists, necessarily happens or exists as the consequence of a previous state of things. This law cannot be proven. It must be taken, *a priori*, as an axiom; but once accepted as a truth it does away with the belief of a capricious ruling power, and even if the strongest disbeliever of the law may deny its truth in theory he invariably applies it in practice during his daily occupation in life.

All future human activity is more or less influenced by past and present conditions. Modern historical writings, as for instance the works of the brilliant Italian historian, Ferrero, always seek to connect past events with present social and economic conditions. Likewise great and constructive statesmen in trying to shape the destinies of nations always reckon with past and present events and conditions. We often hear the term, "a man with foresight," applied to leading financiers and statesmen. This does not mean that such men are gifted with a vision of the future, but simply that they, with a detailed and thorough knowledge of past and present events, associated with the particular undertaking in which they are interested, have drawn conclusions in regard to a future state of affairs. For example, when the Canadian Pacific officials, in the early eighties, chose Vancouver as the western terminal for the transcontinental railroad, at a time when practically the whole site of the present metropolis of western Canada was only a vast timber tract, they realized that the conditions then prevailing on this particular spot—the excellent shipping facilities, the favorable location in regard to the Oriental trade, and the natural wealth of the surrounding country—would bring forth a great city, and their predictions came true.

Predictions with regard to the future must be taken seriously only when they are based upon a thorough knowledge of past and present events and conditions. Prophecies, taken in a purely biblical sense of the term and viewed from the law of causality, are mere guesses which may come true and may not. A prophet can hardly be called more than a successful guesser. Whether there have been persons gifted with a purely prophetic vision is a question which must be left to the theologians to wrangle over.

**3. Hypothetical Judgments.**—Any person with ordinary intellectual faculties may, however, predict certain future events with absolute certainty by a simple application of the principle of hypothetical judgment. The typical form of the hypothetical judgment is as follows: If a certain condition exists, or if a certain event takes place then another definite event will surely follow. Or if *A* exists *B* will invariably follow.

Mathematical theorems are examples of hypothetical judgments. Thus in the geometry of the plane we start with certain ideas (axioms) about the line and plane. From these axioms we then deduce the theorems by mere hypothetical judgments. Thus in the Euclidian geometry we find the axiom of parallel lines, which assumes that through a point only one line can be drawn parallel to another given line, and from this assumption we then deduce the theorem that the sum of the angles in a triangle is  $180^\circ$ . But it must be borne in mind that this proof is valid only on the assumption of the actual existence of such lines. If we could prove directly by logical reasoning or by actual measurement, that the sum of the angles in any triangle is equal to  $180^\circ$ , then we would be able to prove the above theorem, the so-called "hole in geometry," independently of the axiom of parallel lines.

A Russian mathematician, Lobatschewsky, on the other hand, assumed that through a single point an infinite number of parallels might be drawn to a previously given line, and from this assumption he built up a complete and valid geometry of his own. Still another mathematician, Riemann, assumed that no lines were parallel to each other, and from this produced a perfectly valid surface geometry of the sphere.

As examples of hypothetical judgment we have the two following well-known theorems from elementary geometry and algebra. If one of the angles of a triangle is divided into two parts, then the line of division intersects the opposite side. If a decadian number is divided by 5 there is no remainder from the division.

In natural science, hypothetical judgments are founded on certain occurrences (phenomena) which, without exception, have taken place in the same manner, as shown by repeated observations. The statement that a suspended body will fall when its support is removed is a hypothetical judgment derived from actual experience and observation.

**4. Hypothetical Disjunctive Judgments.**—In hypothetical judgments we are always able to associate cause and effect. It happens frequently, however, that our knowledge of a certain complex of present conditions and actions is such that we are not able to tell beforehand the resulting consequences or effects of such conditions and actions, but are able to state only that either an event  $E_1$  or an event  $E_2$ , etc., or an event  $E_n$  will happen. This represents a hypothetical disjunctive judgment whose typical form is: If  $A$  exists either  $E_1$ ,  $E_2$ ,  $E_3$ ,  $\dots$  or  $E_n$  will happen.

If we take a die, *i. e.*, a homogeneous cube whose faces are marked with the numbers from one to six, and make an ordinary throw, we are not able to tell beforehand which side will turn up. True, we have here again a previous state of things, but the conditions do not allow such a simple analysis as the cases we have hitherto considered under the purely hypothetical judgment. Here a multitude of causes influence the final result—the weight and centre of gravity of the die, the infinite number of possible movements of the hand which throws the die, the force of contact with which the die strikes the table, the friction, etc. All these causes are so complex that our minds are not afforded an opportunity to grasp and distinguish the impulses that determine the fall of the die. In other words we are not able to say, *a priori*, which face will appear. We only know for certain that either 1, 2, 3, 4, 5, or 6 will appear. If a line is drawn through the vertex of a triangle, it either intersects the opposite side or it does not. If a number is divided by 5 the division either gives

only an integral number or leaves a remainder. If an opening is made in the wall of a vessel partly filled with water, then either the water escapes or remains in the vessel. All the above cases are examples of hypothetical disjunctive judgments.

The four cases show, however, a common characteristic. They all have a certain partial domain, where one of the mutually exclusive events is certain to happen, while the other partial domain will bring forth the other event, and the total area of action embraces both events. Taking the triangle, we notice that the lines may pass through all the points inside of an angle of  $360^\circ$ , but only the lines falling inside the internal vertical angle,  $\varphi$ , of the triangle will produce the event in question, namely the line intersecting the opposite side. There will be an outflow from the vessel only if the hole is made in that part of the wall which is touched by the fluid.

All problems do not allow of such simple analysis, however, as will be seen from the following example. Suppose we have an urn containing 1 white and 2 black balls and let a person draw one from the urn. The hypothetical disjunctive judgment immediately tells us that the ball will be either black or white, but the particular domain of each event cannot be limited to the fixed border lines of the former examples. Any one of the balls may occupy an infinite number of positions, and furthermore we may imagine an infinite number of movements of the hand which draws the ball, each movement being associated with a particular point of position of the ball in the urn. If we now assume each of the three balls to have occupied all possible positions in the urn, each point of position being associated with its proper movement of the hand, it is readily seen that a black ball will be encountered twice as often as a white ball in a particular point of position in the urn, and for this reason any particular movement of the hand which leads to this point of position grasps a black ball twice as often as a white ball.

**5. General Definition of the Probability of an Event.**—All the above examples have shown the following characteristics:

(1) A total general region or area of action in which all actions may take place, this total area being associated with all possible events.

*field of variation*

(2) A limited special domain in which the associated actions produce a special event only.

If these areas and domains, as in the above cases, are of such a nature that they allow a purely quantitative determination, they may be treated by mathematical analysis. We define now, without entering further into its particular logical significance, the ratio of the second special and limited domain to the first total region or area as the probability of the happening of the event,  $E$ , associated with domain No. 2.

We must, however, hasten to remark that it is only in a comparatively few cases that we are able, *a priori*, to make such a segregation of domains of actions. This may be possible in purely abstract examples, as for instance in the example of the division of the decadian number by 5. But in all cases where organic life enters as a dominant factor we are unable to make such sharp distinctions. If we were asked to determine the probability of an  $x$ -year-old person being alive one year from now, we should be able to form the hypothetical disjunctive judgment: An  $x$ -year-old person will be either alive or dead one year from now. But a further segregation into special domains as was the case with the balls in the urn is not possible. Many extremely complex causes enter into such a determination; the health of the particular person, the surroundings, the daily life, the climate, the social conditions, etc. Our only recourse in such cases is to actual observation. By observing a large number of persons of the same age,  $x$ , we may, in a purely empirical way, determine the rate of death or survival. Such a determination of an unknown probability is called an empirical probability. An empirical probability is thus a probability, into the determination of which actual experience has entered as a dominant factor.

**6. Equally Likely Cases.**— The main difficulty, in the application of the above definition of probability, lies in the determination of the question whether all the events or cases taking place in the general area of action may be regarded as equally likely or not. Two diametrically opposite views have here been brought forward by writers on probabilities. One view is based upon the principle which in logic is known as the principle of

"insufficient reason," while the other view is based upon the principle of "cogent reason." The classical writers on the theory of probability, such as Jacob Bernoulli and Laplace, base the theory on the principle of insufficient reason exclusively. Thus Bernoulli declares the six possible cases by the throw of a die to be equally likely, since "on account of the equal form of all the faces and on account of the homogeneous structure and equally arranged weight of the die, there is no reason to assume that any face should turn up in preference to any other." In one place Laplace says that the possible cases are "cases of which we are equally ignorant," and in another place, "we have no reason to believe any particular case should happen in preference to any other."

The opposite view, based on the principle of cogent reason, has been strongly endorsed in an admirable little treatise by the German scholar, Johannes von Kries.<sup>1</sup> Von Kries requires, first of all, as the main essential in a logical theory of probability, that "the arrangement of the equally likely cases must have a cogent reason and not be subject to arbitrary conditions."

In several illustrative examples, von Kries shows how the principle of insufficient reason may lead to different and paradoxical results. The following example will illustrate the main points in von Kries's criticism. Suppose we be given the following problem: Determine the probability of the existence of human beings on the planet Mars. By applying the first mentioned principle our reasoning would be as follows: We have no more reason to assume the actual existence of man on the planet than the complete absence. Hence the probability for the non-existence of a human being, is equal to  $\frac{1}{2}$ . Next we ask for the probability of the presence or non-presence of another earthly mammal, say the elephant. The answer is the same,  $\frac{1}{2}$ . Now the probability for the absence of both man and elephant on the planet is  $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ .<sup>2</sup> The probability for the absence of a third mammal, the horse, is also  $\frac{1}{2}$ , or the probability for the absence of man, elephant, and horse is equal to  $(\frac{1}{2})^3 = \frac{1}{8}$ . Proceeding in the same manner for all mammals we obtain a very small proba-

<sup>1</sup> "Die Principien der Wahrscheinlichkeitsrechnung." Berlin, 1886.

<sup>2</sup> See the chapter on multiplication of probabilities.

bility for the complete absence of all mammals on Mars, or a very large probability, almost equal to certainty, that the planet harbors at least one mammal known on our planet, an answer which certainly does not seem plausible. But we might as well have put the question from the start: what is the probability of the existence or absence of any one earthly mammal on Mars? The principle of insufficient reason when applied directly would here give the answer  $\frac{1}{2}$ , while when applied in an indirect manner the same method gave an answer very near to certainty.

An urn is known to contain white and black balls, but the number of the balls of the two different colors is unknown. What is the probability of drawing a white ball? The principle of insufficient reason gives us readily the answer:  $\frac{1}{2}$ , while the principle of cogent reason would give the same answer only if it were known a priori that there were equal numbers of balls of each color in the urn before the drawing took place. Since this knowledge is not present a priori, we are not able to give any answer, and the problem is considered outside the domain of probabilities. There is no doubt that the principle advocated by von Kries is the only logical one to apply, and a recent treatise on the theory of probability by Professor Bruhns of Leipzig<sup>1</sup> also gives the principle of cogent reason the most prominent place. On the other hand it must be admitted that if the principle was to be followed consistently in its very extreme it would of course exclude many problems now found in treatises on probability and limit the application of our theory considerably in scope. Still, however, we must agree with von Kries that it seems very foolhardy to assign cases of which we are absolutely in the dark, as being equally likely to occur. This very principle of insufficient reason is in very high degree responsible for the somewhat absurd answers to questions on the so-called "inverse probabilities," a name which in itself is a great misnomer. We shall later in the chapter on "a posteriori" probabilities discuss this question in detail. At present we shall only warn the student not to judge cases of which he has no knowledge whatsoever to be equally likely to occur. The old rule "experience is the best teacher" holds here, as everywhere else.

<sup>1</sup> "Kollektivmasslehre and Wahrscheinlichkeitsrechnung," Leipzig, 1903.

7. **Objective and Subjective Probabilities.**—In this connection it is interesting to note the lucid remarks by the Danish statistician, Westergaard. "By every well arranged game of chance, by lotteries, dice, etc.," Westergaard says, "everything is arranged in such a way that the causes influencing each draw or throw remain constant as far as possible. The balls are of the same size, of the same wood, and have the same density; they are carefully mixed and each ball is thus apparently subject to the influences of the same causes. However, this is not so. Despite all our efforts the balls are different. It is impossible that they are of exactly mathematically spherical form. Each ball has its special deviation from the mathematical sphere, its special size and weight. No ball is absolutely similar to any one of the others. It is also impossible that they may be situated in the same manner in the bag. In short there is a multitude of apparently insignificant differences which determine that a certain definite ball and none of the other balls may be drawn from the bag. If such inequalities did not exist one of two things would happen. Either all balls would turn up simultaneously or also they would all remain in the bag. Many of these numerous causes are so small that they perhaps are invisible to the naked eye and completely escape all calculations, but by mutual action they may nevertheless produce a visible result."

It thus appears that a rigorous application of the principle of cogent reason seems impossible. However, a compromise between this principle and that of the principle of insufficient reason may be effected by the following definition of equally possible cases, viz.: *Equally possible cases are such cases in which we, after an exhaustive analysis of the physical laws underlying the structure of the complex of causes influencing the special event, are led to assume that no particular case will occur in preference to any other.* True, this definition introduces a certain subjective element and may therefore be criticized by those readers who wish to make the whole theory of probabilities purely objective. Yet it seems to me preferable to the strict application of the principle of equal distribution of ignorance. Take again the question of the probability of the existence of human beings on the planet Mars. The principle of equal distribution of ignorance

readily gives us without further ado the answer  $\frac{1}{2}$ . Modern astrophysical researches have, however, verified physical conditions on the planet which make the presence of organic life quite possible, and according to such an eminent authority as Mr. Lowell, perhaps absolutely certain. Yet these physical investigations are as yet not sufficiently complete, and not in such a form that they may be subjected to a purely quantitative analysis as far as the theory of probabilities is concerned. Viewed from the standpoint of the principle of cogent reason any attempt to determine the numerical value of the above probability must therefore be put aside as futile. This result, negative as it is, seems, however, preferable to the absolute guess of  $\frac{1}{2}$  as the probability.

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## CHAPTER II.

### HISTORICAL AND BIBLIOGRAPHICAL NOTES.

**8. Pioneer Writers.**—The first attempt to define the measure of a probability of a future event is credited to the Greek philosopher, Aristotle. Aristotle calls an event probable when the majority, or at least the majority of the most intellectual persons, deem it likely to happen. This definition, although not allowing a purely quantitative measurement, makes use of a subjective judgment.

The first really mathematical treatment of chance, however, is given by the two Italian mathematicians, Cardano and Galileo, who both solved several problems relating to the game of dice. Cardano, aside from his mathematical occupation, was also a professional gambler and had evidently noticed that in all kinds of gambling houses cheating was often resorted to. In order that the gamester might be fortified against such cheating practices, Cardano wrote a little treatise on gambling wherein he discussed several mathematical questions connected with the different games of dice as played in the Italian gambling houses at that time. Galileo, although not a professional gambler, was often consulted by a certain Italian nobleman on several problems relating to the game of dice, and fortunately the great scholar has left some of his investigations in a short memoir. In the same manner the two great French mathematicians, Pascal and Fermat, were often asked by a professional gamester, the chevalier de Mere, to apply their mathematical skill to the solution of different gambling problems. It was this kind of investigation which probably led Pascal to the discovery of the arithmetical triangle, and the first rudiments of the combinatorial analysis, which had its origin in probability problems, and which later evolved into an independent branch of mathematical analysis.

One of the earliest works from the illustrious Dutch physicist, Huyghens, is a small pamphlet entitled "*de Ratiociniis in Ludo Aleæ*," printed in Leyden in the year 1657. Huyghens' tract is

the first attempt of a systematic treatment of the subject. The famous Leibnitz also wrote on chance. His first reference to a mathematical probability is perhaps in a letter to the philosopher, Wolff, wherein he discusses the summation of the infinite series  $1 - 1 + 1 - 1 + \dots$ . Besides he solved several problems.

**9. Bernoulli, de Moivre and Bayes.**—The first extensive treatise on the theory as a whole is from the hand of the famous Jacob Bernoulli. Bernoulli's book, "*Ars Conjectandi*," marks a revolution in the whole theory of chance. The author treats the subject from the mathematical as well as from a philosophical point of view, and shows the manifold applications of the new science to practical problems. Among other important theorems we here find the famous proposition which has become known as the Bernoulli Theorem in the mathematical theory of probabilities. Bernoulli's work has recently been translated from the Latin into German,<sup>1</sup> and a student who is interested in the whole theory of probability should not fail to read this masterly work.

The English mathematicians were the next to carry on the investigations. Abraham de Moivre, a French Huguenot, and one of the most remarkable mathematicians of his time, wrote the first English treatise on probabilities.<sup>2</sup> This book was certainly a worthy product of the masterful mind of its author, and may, even today, be read with useful results, although the method of demonstration often appears lengthy to the student who is accustomed to the powerful tools of modern analysis. The high esteem in which the work by de Moivre is held by modern writers, is proven by the fact that E. Czuber, the eminent Austrian mathematician and actuary, so recently as two years ago translated the book into German. A certain problem (see Chap. IV) still goes under the name of "The Problem of de Moivre" in the modern literature on probability. A contemporary of de Moivre, Stirling, contributed also to the new branch of mathematics, and his name also is immortalized in the theory of probability by the formula which bears his name, and by which we are able to express large factorials to a very accurate degree of approximation. The third important English contributor is

<sup>1</sup> *Ars Conjectandi*, Ostwald's Klassiker No. 108, Leipzig, 1901.

<sup>2</sup> de Moivre: "*The Doctrine of Chances*," London, 1781.

the Oxford clergyman, T. Bayes. Bayes' treatise, which was published after his death by Price, in *Philosophical Transactions* for 1764, deals with the determination of the a posteriori probabilities, and marks a very important stepping stone in our whole theory. Unfortunately the rule known as Bayes' Rule has been applied very carelessly, and that mostly by some of Bayes' own countrymen; so the whole theory of Bayes has been repudiated by certain modern writers. A recent contribution by the Danish philosophical writer, Dr. Kroman, seems, however, to have cleared up all doubts on the subject, and to have given Bayes his proper credit.

**10. Application to Statistical Data.**—In the eighteenth century some of the most celebrated mathematicians investigated problems in the theory of probability. The birth of life assurance gave the whole theory an important application to social problems and the increasing desire for the collection of all kinds of statistical data by governmental bodies all over Europe gave the mathematicians some highly interesting material to which to apply their theories. No wonder, therefore, that we in this period find the names of some of the most illustrious mathematicians of that time, such as Daniel Bernoulli, Euler, Nicolas and John Bernoulli, Simpson, D'Alambert and Buffon, closely connected with the solution of problems in the theory of mathematical probabilities. We shall not attempt to give an account of the different works of these scientists, but shall only dwell briefly on the labors of Bernoulli and D'Alambert. In a memoir in the St. Petersburg Academy, Daniel Bernoulli is the first to discuss the so called St. Petersburg Problem, one of the most hotly debated in the whole realm of our science. We may here mention that this problem is today one of the main pillars in the economic treatment of value. Bernoulli introduced in the discussion of the above mentioned problem the idea of the "moral expectation," which under slightly different names appears in nearly all standard writings on economics.

D'Alambert is especially remembered for the critical attitude he took towards the whole theory. Although one of the most brilliant thinkers of his age, the versatile Frenchman made some great blunders in his attempt to criticize the theories of chance.

Buffon's name is remembered because of the needle problem, and he may properly be called the father of the so-called "geometrical" or "local" probabilities.

11. **Laplace and Modern Writers.**—We now come to that resplendent genius in the investigation of the mathematical theory of chance, the immortal Laplace, who in his great work, "*Théorie Analytique des Probabilités*," gave the final mathematical treatment of the subject. This massive volume leaves nothing to be desired and is still today—more than one hundred years after its first publication—a most valuable mine of information and compares favorably with much more modern treatises. But like all mines, it requires to be mined and is by no means easy reading for a beginner. An elementary extract, "*Essai Philosophique des Probabilités*," containing the more elementary parts of Laplace's greater work and stripped of all mathematical formulas has recently appeared in an English translation.

Among later French works, Cournot's "*Exposition de la Théorie des Chances et des Probabilités*" (1843), treated the principal questions in the application of the theory to practical problems in sociology. In 1837 Poisson published his "*Recherches sur les Probabilités*" in which he for the first time proved the famous theorem which bears his name. Poisson and his Belgian contemporary, Quetelet, made extensive use of the theory in the treatment of statistical data.

Among the most recent French works, we mention especially Bertrand's "*Calcul des Probabilités*" (Paris, 1888), Poincaré's "*Calcul des Probabilités*" (Paris, 1896), and Borel's "*Calcul des Probabilités*" (Paris, 1901). We especially recommend Poincaré's brilliant little treatise to every student who masters the French language, as this book makes no departure from the lively and elucidating manner in which this able mathematical writer treated the numerous subjects on which he wrote during his long and brilliant career as a mathematician.

Of Russian writers, the mathematician, Tchebycheff, has given some extensive general theorems relating to the law of large numbers. Unfortunately Tchebycheff's writings are for the most part scattered in French, German, Scandinavian and

Russian journals, and thus are not easily accessible to the ordinary reader. A Russian artillery officer, Sabudski, has recently published a treatise on ballistics in German, wherein he extends the views formulated by Tchebycheff.

Of Scandinavian writers we mention T. N. Thiele, who probably was the first to publish a systematic treatise on skew curves.<sup>1</sup> An abridged edition of this very original work has recently been translated into English.<sup>2</sup> The Dane, Westergaard, is the author of the most extensive and thorough treatise on vital statistics which we possess at the present time. Westergaard's work has recently been translated into German,<sup>3</sup> and is strongly recommended to the student of vital statistics on account of his clear and attractive style of presenting this important subject.

The Swedish mathematicians Charlier and Gylden have published a series of memoirs in different Scandinavian journals and scientific transactions. We may also, in this category, mention the numerous small articles by the eminent Danish actuary, Dr. Gram.

While the German mathematicians in general are the most fertile writers on almost every branch of pure and applied mathematics, they have not shown much activity in the theory of mathematical probability except in the past ten years. But during that time there has appeared at least a dozen standard works in German. Among these, the lucid and terse treatise by E. Czuber, the Austrian actuary and mathematician, is especially attractive to the beginner on account of the systematic treatment of the whole subject.<sup>4</sup> A very original treatment is offered by H. Bruhns in his "Kollektivmasslehre und Wahrscheinlichkeitsrechnung" (Leipzig, 1903). Among the German works, we may also mention the book by Dr. Norman Herz in "Sammlung Schubert," and an excellent little work by Hack in the small pocket edition of "Sammlung Göschen." The theory of skew curves and correlation is presented by Lipps and Bruhns in extensive treatises.

<sup>1</sup> "Almindelig Iagttagelseslaere," Copenhagen, 1884.

<sup>2</sup> "Theory of Observations," London, 1903.

<sup>3</sup> "Mortalität und Morbilität," Jena, 1902.

<sup>4</sup> E. Czuber, "Wahrscheinlichkeitsrechnung," Leipzig, 1908 and 1910, 2 volumes.

We finally come to modern English writers on the subject. After the appearance of de Moivre's "Doctrine of Chances" the first work of importance was the book by de Morgan "An Essay on the Theory of Probabilities." The latest text-book is Whitworth's "Choice and Chance" (Oxford Press, 1904); but none of these works, although very excellent in their manner of treatment of the subject, comes up to the French, Scandinavian, and German text-books. Nevertheless, some of the most important contributions to the whole theory have been made by the English statisticians and mathematicians, Crofton, Pearson, and Edgeworth. Especially have frequency curves and correlation methods introduced by Professor Karl Pearson been very extensively used in direct applications to statistical and biological problems. Of purely statistical writers, we may mention G. Udny Yule, who has published a short treatise entitled "Theory of Statistics" (London, 1911). Numerous excellent memoirs have also appeared in the different English and American mathematical journals and statistical periodicals, especially in the quarterly publication, *Biometrika*, edited by Professor Karl Pearson.

In the above brief sketch, we have only mentioned the most important contributors to the theory of probabilities proper. Numerous able writers have written on the related subject of least squares, the mathematical theory of statistics and insurance mathematics. We shall not discuss the works of these investigators at the present stage. Each of the most important works in the above mentioned branches will receive a short review in the corresponding chapters on statistics and assurance mathematics. The readers interested in the historical development of the theory of probabilities are advised to consult the special treatises on this subject by Todhunter and Czuber.<sup>1</sup>

<sup>1</sup> After this chapter had gone to press I notice that a treatise by the eminent English scholar, Mr. Keynes, is being prepared by The Macmillan Co. In this connection I wish also to call attention to the recent publication by Bachelier (*Calcul des probabilités*, 1912), a work planned on a broad and extensive scale.—A. F.

## CHAPTER III.

### THE MATHEMATICAL THEORY OF PROBABILITIES.

**12. Definition of Mathematical Probability.**—"If our positive knowledge of the effect of a complex of causes is such that we may assume, a priori,  $t$  cases as being equally likely to occur, but of which only  $f$ , ( $f < t$ ), cases are favorable in causing the event,  $E$ , in which we are interested, then we define the proper fraction:  $f/t = p$  as the mathematical probability of the happening of the event,  $E$ " (Czuber). We might also have defined an a priori probability as the ratio of the equally favorable cases to the co-ordinated possible cases.

As is readily seen, this definition assumes a certain a priori knowledge of the possible and favorable conditions of the event in question, and the probability thus defined is therefore called "a priori probability." Denoting the event by the symbol,  $E$ , we express the probability of its occurrence by the symbol  $P(E)$ , and the probability of its non-occurrence by  $P(\bar{E})$ . Thus if  $t$  is the total number of equally possible cases and  $f$  the number of favorable cases for the event, we have:

$$P(E) = \frac{f}{t} = p,$$

and

$$P(\bar{E}) = \frac{t-f}{t} = 1 - \frac{f}{t} = 1 - p = 1 - P(E).$$

This relation evidently gives us:  $P(E) + P(\bar{E}) = 1$ , which is the symbolic expression for the hypothetical disjunctive judgment that the event  $E$  will either happen or not happen. If  $f = t$ , we have:

$$P(E) = \frac{t}{t} = 1,$$

which is the symbol for the hypothetical judgment that if  $A$  exists,  $E$  will surely happen. Similarly if  $f = 0$ , we get

$$P(E) = \frac{0}{t} = 0,$$

or the symbol for the hypothetical judgment: If  $A$  exists,  $E$  will not happen, or what is the same,  $\bar{E}$  will happen.

As we have already mentioned, in an a priori determination of a probability, special stress must be laid upon the requirement that all possible cases must be equally likely to occur. The enumeration of these cases is by no means so easy as may appear at first sight. Even in the most simple problems where there can be doubt about the possible cases being equally likely to occur, it is very easy to make a mistake, and some of the most eminent mathematicians and most acute thinkers have drawn erroneous conclusions in this respect. We shall give a few examples of such errors from the literature on the subject of the theory of probabilities, not on account of their historical interest alone, but also for the benefit of the novice who naturally is exposed to such errors.

13. **Example 1.**—An Italian nobleman, a professional gambler and an amateur mathematician, had, by continued observation of a game with three dice, noticed that the sum of 10 appeared more often than the sum of 9. He expressed his surprise at this to Galileo and asked for an explanation. The nobleman regarded the following combinations as favorable for the throw of 9:

|   |   |   |
|---|---|---|
| 1 | 2 | 6 |
| 1 | 3 | 5 |
| 1 | 4 | 4 |
| 2 | 2 | 5 |
| 2 | 3 | 4 |
| 3 | 3 | 3 |

and for the throw of 10 the six combinations of:

|   |   |   |
|---|---|---|
| 1 | 3 | 6 |
| 1 | 4 | 5 |
| 2 | 2 | 6 |
| 2 | 3 | 5 |
| 2 | 4 | 4 |
| 3 | 3 | 4 |

Galileo shows in a treatise entitled "Considerazione sopra il giuco dei dadi" that these combinations cannot be regarded as being equally likely. By painting each of the three dice with the different color it is easy to see that an arrangement such as 1 2 6 can be produced in 6 different ways. Let the colors be white, black and red respectively. We may then make the following arrangements:

| White | Black | Red |
|-------|-------|-----|
| 1     | 2     | 6   |
| 1     | 6     | 2   |
| 2     | 1     | 6   |
| 2     | 6     | 1   |
| 6     | 1     | 2   |
| 6     | 2     | 1   |

which gives  $3! = 6$  different arrangements. The arrangements of 1 4 4 can be made as follows:

| White | Black | Red |
|-------|-------|-----|
| 1     | 4     | 4   |
| 4     | 1     | 4   |
| 4     | 4     | 1   |

which gives 3 different arrangements. The arrangements of 3 3 3 can be made in one way only. By complete enumeration of equally favorable cases we obtain the following scheme:

| Sum 9   | cases     | Sum 10  | cases     |
|---------|-----------|---------|-----------|
| 1, 2, 6 | 6         | 1, 3, 6 | 6         |
| 1, 3, 5 | 6         | 1, 4, 5 | 6         |
| 1, 4, 4 | 3         | 2, 2, 6 | 3         |
| 2, 2, 5 | 3         | 2, 3, 5 | 6         |
| 2, 3, 4 | 6         | 2, 4, 4 | 3         |
| 3, 3, 3 | 1         | 3, 3, 4 | 3         |
|         | <u>25</u> |         | <u>27</u> |

The total number of equally possible cases by the different arrangements of the 18 faces on the dice is  $6^3 = 216$ . The probability of throwing 9 with three dice is therefore  $\frac{25}{216}$ , of throwing 10 =  $\frac{27}{216} = \frac{1}{8}$ .

14. **Example 2.**—D’Alambert, the great French mathematician and natural philosopher and one of the ablest thinkers of his time, assigned  $\frac{3}{4}$  as the probability of throwing head at least once in two successive throws with a homogeneous coin. D’Alambert reasons as follows: If head appears first the game is finished and a second throw is not necessary. He therefore gives as equally possible cases (we denote head by  $H$  and tail by  $T$ ):  $H$ ,  $TH$ ,  $TT$ , and determines thus the probability as  $\frac{3}{4}$ . Where then is the error of D’Alambert? At first glance the chain of reasoning seems perfect. There are altogether three possible cases of which two are in favor of the event. But are the three cases equally likely? To throw head in a single throw is evidently not the same as to throw head in two successive throws. D’Alambert has left out of consideration the fact that a double throw is allowed. The following analysis shows all the equally possible cases which may occur:

$$HH, HT, TH, TT.$$

Three of those cases favor the event. Hence we have:

$$P(E) = p = \frac{3}{4}.$$

We shall return to this problem at a later stage under the discussion of the law of large numbers.

The examples quoted have already shown that the enumeration of the equally likely cases requires a sharp distinction between the different combinations and arrangements of elements. In other words, the solution of the problems requires a knowledge of permutations and combinations. We assume here that the reader is already acquainted with the elements and formulas from the combinatorial analysis and shall therefore proceed with some more illustrations. In the following, when employing the binomial coefficients, we shall use the notation  $\binom{m}{k}$  instead of  ${}^mC_k$ .

15. **Example 3.**—An urn contains  $a$  white and  $b$  black balls. A person draws  $k$  balls. What is the probability of drawing  $\alpha$  white and  $\beta$  black balls?

$$(\alpha + \beta = k, \quad \alpha \leq a, \quad \beta \leq b)$$

$k$  balls may be drawn from the urn in as many ways as it is possible to select  $k$  elements from  $a + b$  elements, which may be done in

$$t = \binom{a+b}{k} = \binom{a+b}{\alpha+\beta}$$

ways. Furthermore there are  $\binom{a}{\alpha}$  groups of  $\alpha$  white and  $\binom{b}{\beta}$  groups of  $\beta$  black balls. Since each combination of any one group of the first groups with any one group of the second groups is favorable for the event, we have as favorable cases:

$$f = \binom{a}{\alpha} \times \binom{b}{\beta}; \quad \text{or} \quad P(E) = \frac{\binom{a}{\alpha} \times \binom{b}{\beta}}{\binom{a+b}{\alpha+\beta}}.$$

**Example 4.** A special case of the above problem is the following question which often appears in the well known game of whist. What are the respective chances that 0, 1, 2, 3, 4 aces are held by a specified player? There are altogether 52 cards in the game equally distributed among 4 players. Of these cards 4 are aces and 48 are non-aces. Hence we have the following values for  $a$ ,  $b$ ,  $k$ ,  $\alpha$  and  $\beta$ .

$a = 4$ ,  $b = 48$ ,  $k = 13$ ,  $\alpha = 0, 1, 2, 3, 4$ ,  $\beta = 13, 12, 11, 10, 9$ .

Substituting in the above formula we get:

$$p_0 = \binom{4}{0} \times \binom{48}{13} \div \binom{52}{13} = \frac{82251}{270725}$$

$$p_1 = \binom{4}{1} \times \binom{48}{12} \div \binom{52}{13} = \frac{118807}{270725}$$

$$p_2 = \binom{4}{2} \times \binom{48}{11} \div \binom{52}{13} = \frac{57798}{270725}$$

$$p_3 = \binom{4}{3} \times \binom{48}{10} \div \binom{52}{13} = \frac{11154}{270725}$$

$$p_4 = \binom{4}{4} \times \binom{48}{9} \div \binom{52}{13} = \frac{715}{270725}.$$

A hypothetical disjunctive judgment immediately tells us that in

a game of whist a specified player must either hold 0, 1, 2, 3 or 4 aces. Any such judgment is certain to come true. Hence by adding the 5 above computed probabilities we obtain a check for the accuracy of our calculations. The actual addition of the numerical values of  $p_0$ ,  $p_1$ ,  $p_2$ ,  $p_3$ , and  $p_4$  gives us unity which is the mathematical symbol for certainty. Gauss, the renowned German mathematician and astronomer, was an eager whist player. During his forty-eight years of residence in the university town of Göttingen almost every evening he played a rubber of whist with some friends among the university professors. He kept a careful record of the distribution of the aces in each game. After his death these records were found among his papers, headed "Aces in Whist." The actual records agree with the results computed above.

16. **Example 5.**—An urn contains  $n$  similar balls. A part of or all the balls are drawn. What is the probability of drawing an even number of balls?

One ball may be drawn in as many ways as there are balls, two balls in as many ways as we may select two elements out of  $n$  elements, and so on. Hence we have for the total number of equally possible cases:

$$t = \binom{n}{1} + \binom{n}{2} + \binom{n}{3} + \cdots + (+1)^n \binom{n}{n}.$$

We have now:

$$(1 + 1)^n = 1 + \binom{n}{1} + \binom{n}{2} + \cdots + \binom{n}{n},$$

and

$$(1 - 1)^n = 1 - \binom{n}{1} + \binom{n}{2} - \cdots + (-1)^n \binom{n}{n}.$$

The number of favorable cases is given by the expansion:

$$f = \binom{n}{2} + \binom{n}{4} + \cdots.$$

The expression for  $t$  is the binominal coefficients less unity. Hence we have:

$$t = (1 + 1)^n - 1 = 2^n - 1.$$

If we add the two expansions of  $(1 + 1)^n$  and  $(1 - 1)^n$  and then

subtract 2 we get the expansion for  $2f$ . Hence we have:

$$2f = [(1 + 1)^n + (1 - 1)^n - 2] \therefore f = 2^{n-1} - 1.$$

Thus we shall have as the probability of drawing an even number of balls:

$$p = \frac{2^{n-1} - 1}{2^n - 1}$$

while for an uneven number:

$$q = 1 - p = \frac{2^{n-1}}{2^n - 1}.$$

We notice that the probability of drawing an uneven number of balls is larger than the probability of drawing an even number. This apparently strange result is easily explained without the aid of algebra from the fact that when the urn contains one ball only, we cannot draw an even number. Hence we have  $p = 0$ ,  $q = 1$ . With two balls we may draw an uneven number in two ways and an even number in one way, thus  $p = \frac{1}{3}$ , and  $q = \frac{2}{3}$ . The greater weight of  $q$  remains when  $n$  is finite; only when

$$n = \infty, \quad p = q = \frac{1}{2}.$$

**17. Example 6.**—A box contains  $n$  balls marked 1, 2, 3,  $\dots$   $n$ . A person draws  $n$  balls in succession and none of the balls thus drawn is put back in the urn. Each drawing is consecutively marked 1, 2, 3,  $\dots$   $n$  on  $n$  cards. What is the probability that no ball marked  $\alpha$  ( $\alpha = 1, 2, 3, \dots, n$ ) appears simultaneously with a drawing card marked  $\alpha$ ?

The number of equally possible cases is simply the number of permutations of  $n$  elements which is equal to  $n!$

The number of favorable cases is given by the total number of derangements or relative permutations of  $n$  elements, i. e., such permutations wherein the numbers from 1 to  $n$  do not appear in their natural places. The formula for such relative permutations was first given by Euler in a memoir of the St. Petersburg Academy entitled "*Quaestio Curiosa ex Doctrina Combinationis.*" Euler makes use of a recursion formula. A German mathematician, Lampe, has, however, derived the formula in a simpler manner in "*Grunert's Archives*" for 1884.

Lampe denotes by the symbol  $\varphi(1)$  the number of permutations wherein 1 does not appear in its natural place. By letting 1 remain fixed in the first place we obtain  $(n-1)!$  permutations of the other remaining elements, or:

$$\varphi(1)_n = n! - (n-1)!$$

permutations where 1 is out of place. Of these permutations there are, however, a number wherein 2 appears in its natural place. If we let 2 remain fixed in this place we shall have:

$$\varphi(1)_{n-1} = (n-1)! - (n-2)!$$

permutations wherein 2 is in its place but 1 out of place, there remains thus:

$$\varphi(2)_n = \varphi(1)_n - \varphi(1)_{n-1} = n! - 2(n-1)! + (n-2)!$$

permutations in which neither 1 nor 2 is in its natural place. Letting 3 remain fixed in its place, the remaining  $n-1$  elements give:

$$(n-1)! - 2(n-2)! + (n-3)!$$

cases where 3 is in its place but 1 and 2 are not. Accordingly there will be:

$$\varphi(3)_n = \varphi(2)_n - \varphi(2)_{n-1} = n! - 3(n-1)! + 3(n-2)! - (n-3)!$$

permutations in which none of the three elements 1, 2, and 3 is in its place. The complete deduction gives us now for the number  $r$ :

$$\begin{aligned} \varphi(r)_n = n! - \binom{r}{1} (n-1)! + \binom{r}{2} (n-2)! - \dots \\ + (-1)^r \binom{r}{r} (n-r)! \end{aligned}$$

arrangements in which none of the numbers 1, 2, 3,  $\dots$   $r$  is in its place. Hence the required probability is:

$$\begin{aligned} \frac{\varphi(r)_n}{n!} = 1 - \binom{r}{1} \frac{1}{n} + \binom{r}{2} \frac{1}{n(n-1)} - \dots \\ + (-1)^r \binom{r}{r} \frac{1}{n(n-1) \dots (n-r+1)}; \end{aligned}$$

when  $n = r$  the above expression becomes:

$$p = 1 - \frac{1}{1} + \frac{1}{1.2} - \frac{1}{1.2.3} + \dots + (-1)^n \frac{1}{1.2.3 \dots n}$$

or the probability that none of the balls appear in its numerical order.

When  $n = \infty$  the above expression converges towards  $e^{-1}$  as a limit. Since the series is rapidly convergent, we may therefore as an approximate value let

$$p = e^{-1} = 0.36788 \dots$$

The probability that at least one ball appears in numerical order is

$$q = 1 - p = 0.63213 \dots$$

## CHAPTER IV.

### THE ADDITION AND MULTIPLICATION THEOREMS IN PROBABILITIES.

**18. Systematic Treatment by Laplace.**—The reader will readily have noticed that the problems hitherto considered have been solved by a direct application of the fundamental definition of a mathematical probability. Almost every branch of pure and applied mathematics has originated in this manner. A few isolated problems, apparently having no mutual connection whatsoever, have presented themselves to different mathematicians. As the number of problems increased, there was found to exist a certain inner relation between them, and from the mere isolated cases there grew a systematic treatment of an entirely new subject.

The theory of probabilities had its origin in games; and the different problems that arose, were treated individually. From the time of Galileo and Cardano to the appearance of Laplace's great treatise, a number of celebrated mathematicians such as Pascal, Fermat, Huyghens, De Moivre, Stirling, Bernoulli and others had solved numerous problems, some of these, as we already have seen in the preceding chapter, of a quite complex nature. But none of these mathematicians had hitherto succeeded in giving a systematic treatment of the subject as a whole. All their treatises were, as any one taking the trouble to look over the works of De Moivre and Bernoulli will readily notice, mere collections of examples solved by direct application of our fundamental definition. It remained for Laplace first to give the definite rules to the science by which the solution of a great number of problems, often very complicated, was reduced to the application of a few stable principles, first given in his "*Théorie Analytique des Probabilités*" (Paris, 1812).

**19. Definition of Technical Terms.**—Before entering into a demonstration of Laplace's theorems it will, however, be necessary to explain a few technical terms which seem commonplace

and simple enough but which, nevertheless, must be defined clearly in order to avoid any ambiguity.

In all works on probabilities when speaking of happenings of various events we encounter often the terms, *independent events*, *dependent events* and *mutually exclusive events*. An event  $E$  is said to be independent of another event  $F$  when the actual happening of  $F$  does not influence in any degree whatsoever the probability of the happening of  $E$ . On the other hand, if the probability of  $E$  is dependent on or influenced by the previous happening of  $F$ , then  $E$  is said to be dependent on  $F$ . Finally the two events  $E$  and  $F$  are said to be mutually exclusive when through the occurrence of one of them, say  $F$ , the other event  $E$  cannot take place, or vice versa. We might also in this case consider the two events  $E$  and  $F$  as members of a complete disjunction. In a complete hypothetical disjunctive judgment as "When a die is thrown either 1, 2, 3, 4, 5 or 6 will turn up" each member represents a possible event. Any one of these events is mutually exclusive in respect to the other events of the disjunction.

**20. The Theorem of the Complete or Total Probability, or the Probability of "Either Or."**—When an event,  $E$ , may happen in any one of the  $n$  different and mutually exclusive ways  $E_1, E_2, E_3, \dots E_n$  with the respective probabilities:  $p_1, p_2, p_3, \dots p_n$ , then the probability for the happening of the event,  $E$ , is equal to the sum of the individual probabilities:  $p_1, p_2, p_3, \dots p_n$ .

Proof: The main event,  $E$ , falls in  $n$  groups of subsidiary events of which only one can happen in a single trial but of which any one will bring forth the event  $E$ . Let us by  $t$  denote the total number of equally possible cases. Of these possible cases  $f$  are in favor of the event. This favorable group of cases may now be divided into  $n$  sub-groups of which  $f_1$  are favorable for the happening of  $E_1, f_2$  in favor of  $E_2, f_3$  in favor of  $E_3 \dots f_n$  in favor of  $E_n$ . When we write:

$$P(E) = p = \frac{f}{t} = \frac{f_1 + f_2 + f_3 + \dots + f_n}{t} = \frac{f_1}{t} + \frac{f_2}{t} + \frac{f_3}{t} + \dots + \frac{f_n}{t}.$$

... of the subsidiary events,  $p_1, p_2, p_3, \dots, p_n$ , represents the respective probabilities for the actual occurrence of the subsidiary events,  $E_1, E_2, E_3, \dots, E_n$ . Hence we shall have

$$P(E) = p = p_1 + p_2 + p_3 + \dots + p_n.$$

This theorem is also known as the Addition Theorem of probabilities. Instead of "total probability" the German scholar, Reuschle, has suggested the expressive name of the "either or" probability. The term is well selected when we remember that the event,  $E$ , will happen when either  $E_1$ , or  $E_2$  or  $E_3 \dots$  or  $E_n$  happens.

*Example 7.*—What is the probability to throw 8 with two dice in a single throw?

The total number of ways is  $t = 6^2 = 36$ . The event in question  $E$  is composed of the three subsidiary events favoring the combination of 8:

$$E_1: 6, 2$$

$$E_2: 5, 3$$

$$E_3: 4, 4.$$

Now

$$P(E_1) = \frac{2!}{36} = \frac{1}{18}, \quad P(E_2) = \frac{2!}{36} = \frac{1}{18}, \quad P(E_3) = \frac{1}{36}.$$

Hence

$$P(E) = \frac{1}{18} + \frac{1}{18} + \frac{1}{36} = \frac{5}{36}.$$

**21. Theorem of the Compound Probability or the Probability of "As Well As."**—An event  $E$  may happen when every one of the mutually exclusive events  $E_1, E_2, E_3, \dots, E_n$  has occurred previously. It is immaterial if the  $n$  subsidiary events have happened simultaneously or in succession. But it makes a difference if the events  $E_1, E_2, E_3, \dots, E_n$  are independent, or dependent on each other.

1. *Independent Events.*—The probability,  $P(E) = p$ , for the simultaneous or consecutive appearance of several mutually exclusive events:  $E_1, E_2, \dots, E_n$  is equal to the product:  $p_1 \cdot p_2 \cdot p_3 \cdot \dots \cdot p_n$  of the individual probabilities of the  $n$  events.

*Proof:* Let the number of possible cases entering into the complex that brings forth the event  $E$  be  $t$ . Each of the  $t_1$

possible cases corresponding to the event  $E_1$  may occur simultaneously with each one of the  $t_2$  cases corresponding to the event  $E_2$ . Thus we have altogether  $t_1 \times t_2$  cases falling on  $E_1$  and  $E_2$  at the same time. Continuing in the same way of reasoning it is readily seen that the total number of equally possible cases resulting from the simultaneous occurrence of the events  $E_1, E_2, E_3, \dots E_n$  is equal to  $t_1 \times t_2 \times t_3 \times \dots t_n$ . By applying the same reasoning to the favorable cases we get as their total number:

$$f = f_1 \times f_2 \times f_3 \times \dots f_n.$$

Hence the final probability for the happening of the simultaneous or consecutive appearance of the  $n$  minor events is:

$$P(E) = \frac{f}{t} = \frac{f_1}{t_1} \times \frac{f_2}{t_2} \times \frac{f_3}{t_3} \times \dots \frac{f_n}{t_n} = p_1 \times p_2 \times p_3 \times \dots p_n.$$

*Example 8.*—A card is drawn from a whist deck, another card is drawn from a pinochle deck. What is the probability that they both are aces?

A whist deck contains 52 cards of which four are aces, a pinochle deck 48 cards with 8 aces. Denoting the probabilities of getting an ace from the whist and pinochle decks by  $P(E_1)$  and  $P(E_2)$  respectively we have:

$$P(E) = P(E_1)P(E_2) = \frac{4}{52} \times \frac{8}{48} = \frac{1}{78}.$$

*2. Dependent Events.*—The  $n$  events  $E_1, E_2, E_3, \dots E_n$  are not independent of each other, but are related in such a way that the appearance of  $E_1$  influences  $E_2$ , that event influences in turn  $E_3, E_3$  event  $E_4$  and so on.

The same reason holds as above, and,

$$P(E) = p = p_1 \times p_2 \times p_3 \times \dots p_n.$$

But  $p_2$  means here the probability for the happening of  $E_2$  after the actual occurrence of  $E_1$ ,  $p_3$  the probability for the happening of  $E_3$  after  $E_1$  and  $E_2$  have previously happened, and so on for all  $n$  events.

*Example 9.*—A card is drawn from a whist deck and replaced by a joker, and then a second card is drawn. What is the probability that both cards are aces?

Each of the fractions  $f_\alpha/t$  ( $\alpha = 1, 2, 3, \dots n$ ) represents the respective probabilities for the actual occurrence of the subsidiary events,  $E_1, E_2, E_3, \dots E_n$ . Hence we shall have

$$P(E) = p = p_1 + p_2 + p_3 + \dots + p_n.$$

This theorem is also known as the Addition Theorem of probabilities. Instead of "total probability" the German scholar, Reuschle, has suggested the expressive name of the "either or" probability. The term is well selected when we remember that the event,  $E$ , will happen when either  $E_1$ , or  $E_2$  or  $E_3 \dots$  or  $E_n$  happens.

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Now

$$P(E_1) = \frac{2!}{36} = \frac{1}{18}, \quad P(E_2) = \frac{2!}{36} = \frac{1}{18}, \quad P(E_3) = \frac{1}{36}.$$

Hence

$$P(E) = \frac{1}{18} + \frac{1}{18} + \frac{1}{36} = \frac{5}{36}.$$

**21. Theorem of the Compound Probability or the Probability of "As Well As."**—An event  $E$  may happen when every one of the mutually exclusive events  $E_1, E_2, E_3, \dots E_n$  has occurred previously. It is immaterial if the  $n$  subsidiary events have happened simultaneously or in succession. But it makes a difference if the events  $E_1, E_2, E_3, \dots E_n$  are independent, or dependent on each other.

1. *Independent Events.*—The probability,  $P(E) = p$ , for the simultaneous or consecutive appearance of several mutually exclusive events:  $E_1, E_2, \dots E_n$  is equal to the product:  $p_1 \cdot p_2 \cdot p_3 \cdot \dots p_n$  of the individual probabilities of the  $n$  events.

*Proof:* Let the number of possible cases entering into the complex that brings forth the event  $E$  be  $t$ . Each of the  $t_1$

possible cases corresponding to the event  $E_1$  may occur simultaneously with each one of the  $t_2$  cases corresponding to the event  $E_2$ . Thus we have altogether  $t_1 \times t_2$  cases falling on  $E_1$  and  $E_2$  at the same time. Continuing in the same way of reasoning it is readily seen that the total number of equally possible cases resulting from the simultaneous occurrence of the events  $E_1, E_2, E_3, \dots, E_n$  is equal to  $t_1 \times t_2 \times t_3 \times \dots \times t_n$ . By applying the same reasoning to the favorable cases we get as their total number:

$$f = f_1 \times f_2 \times f_3 \times \dots \times f_n.$$

Hence the final probability for the happening of the simultaneous or consecutive appearance of the  $n$  minor events is:

$$P(E) = \frac{f}{t} = \frac{f_1}{t_1} \times \frac{f_2}{t_2} \times \frac{f_3}{t_3} \times \dots \times \frac{f_n}{t_n} = p_1 \times p_2 \times p_3 \times \dots \times p_n.$$

*Example 8.*—A card is drawn from a whist deck, another card is drawn from a pinochle deck. What is the probability that they both are aces?

A whist deck contains 52 cards of which four are aces, a pinochle deck 48 cards with 8 aces. Denoting the probabilities of getting an ace from the whist and pinochle decks by  $P(E_1)$  and  $P(E_2)$  respectively we have:

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*2. Dependent Events.*—The  $n$  events  $E_1, E_2, E_3, \dots, E_n$  are not independent of each other, but are related in such a way that the appearance of  $E_1$  influences  $E_2$ , that event influences in turn  $E_3, E_3$  event  $E_4$  and so on.

The same reason holds as above, and,

$$P(E) = p = p_1 \times p_2 \times p_3 \times \dots \times p_n.$$

But  $p_2$  means here the probability for the happening of  $E_2$  after the actual occurrence of  $E_1$ ,  $p_3$  the probability for the happening of  $E_3$  after  $E_1$  and  $E_2$  have previously happened, and so on for all  $n$  events.

*Example 9.*—A card is drawn from a whist deck and replaced by a joker, and then a second card is drawn. What is the probability that both cards are aces?

Denoting the two subsidiary events by  $E_1$  and  $E_2$  we have:

$$P(E) = P(E_1)P(E_2) = \frac{4}{52} \cdot \frac{3}{52} = \frac{3}{13 \times 52} = \frac{3}{676}.$$

The two above theorems are known as the multiplication theorems in probabilities. Reuschle has also suggested the name "the as well as probability."

**22. Poincaré's Proof of the Addition and Multiplication Theorem.**—The French mathematician and physicist, H. Poincaré, has derived the above theorems in a new and elegant manner in his excellent little treatise: "Leçons sur le Calcul des Probabilités," Paris, 1896.

Poincaré's proof is briefly as follows:

Let  $E_1$  and  $E_2$  be two arbitrary events.

$E_1$  and  $E_2$  may happen in  $\alpha$  different ways.

$E_1$  may happen but not  $E_2$  in  $\beta$  different ways.

$E_2$  may happen but not  $E_1$  in  $\gamma$  different ways.

Neither  $E_1$  nor  $E_2$  will happen in  $\delta$  different ways.

We assume the total  $\alpha + \beta + \gamma + \delta$  cases to be equally likely to occur.

The probability for the occurrence of  $E_1$  is

$$p_1 = \frac{\alpha + \beta}{\alpha + \beta + \gamma + \delta}.$$

The probability for the occurrence of  $E_2$  is

$$p_2 = \frac{\alpha + \gamma}{\alpha + \beta + \gamma + \delta}.$$

The probability for the occurrence of at least one of the events  $E_1$  and  $E_2$  is

$$p_3 = \frac{\alpha + \beta + \gamma}{\alpha + \beta + \gamma + \delta}.$$

The probability for the occurrence of both  $E_1$  and  $E_2$  is

$$p_4 = \frac{\alpha}{\alpha + \beta + \gamma + \delta}.$$

The probability for the occurrence of  $E_1$  when  $E_2$  has already occurred is

$$p_5 = \frac{\alpha}{\alpha + \gamma}.$$

The probability for the occurrence of  $E_2$  when  $E_1$  has already occurred is

$$p_6 = \frac{\alpha}{\alpha + \beta}.$$

The probability for the occurrence of  $E_1$  when  $E_2$  has not already occurred is

$$p_7 = \frac{\beta}{\beta + \gamma}.$$

The probability for the occurrence of  $E_2$  when  $E_1$  has not already occurred is

$$p_8 = \frac{\gamma}{\gamma + \delta}.$$

We have now the following identical relations:

$$p_1 + p_2 = p_3 + p_4, \quad p_3 = p_1 + p_2 - p_4,$$

i. e., the probability that of two arbitrary events at least one will happen is equal to the probability that the first will happen plus the probability that the second will happen less the probability that both will happen. The particular problem which we may happen to investigate may possibly be of such a nature that the two events  $E_1$  and  $E_2$  cannot happen at the same time, in that case  $p_4 = 0$ , and we get:

$$p_3 = p_1 + p_2$$

In this equation we immediately recognize the addition theorem for two mutually exclusive events. By substitution of the proper values we have furthermore:

$$p_4 = p_2 \cdot p_6 \quad \text{or} \quad p_4 = p_1 \cdot p_8.$$

These equations contain the theorems proved under § 21, of the probability for two mutually dependent events.

**23. Relative Probabilities.**—We shall now finally give an alternative demonstration of the same two theorems. It will, of course, be of benefit to the student to see the subject from as many view points as possible; moreover, the following remarks will contain some very useful hints for the solution of more complicated problems by the application of so-called "relative prob-

abilities" and a few elementary theorems from the calculus of logic. The following paragraphs are mainly based upon a treatise in the Proceedings of the Royal Academy of Saxony, by the German mathematician and actuary, F. Hausdorff.

In our fundamental definition of a mathematical probability for the happening of an event  $E$ , expressed in symbols by  $P(E)$ , as the ratio of the equally favorable and equally possible cases resulting from a general complex of causes, we were able to compute the so-called ordinary or absolute probabilities. But if we, from among the favorable cases and possible cases, select only such as bring forward a certain different event, say  $F$ , then we obtain the "relative probability" for the happening of  $E$  under the assumption that the subsidiary event,  $F$ , has occurred previously. For this relative probability we shall employ the symbol  $P_F(E)$ , which reads "the relative probability of  $E$ , positi  $F$ ." The following problem illustrates the meaning of relative probabilities. If an honor card is drawn from an ordinary deck of cards, what is the probability that it is a king? Denoting the subsidiary event of drawing an honor card by  $F$ , and the main event of drawing a king by  $E$ , we may write the above mentioned probability in the symbolic form:  $P_F(E)$ . If on the other hand we knew a priori that a king was drawn, we may also ask for the probability of having drawn an honor card. Since any king also is an honor card, we may write in symbols:  $P_E(F) = 1$ .

Before entering upon the immediate determination of relative probabilities we shall first define a few symbols from the calculus of logic. We denote first of all the occurrence of an event  $E$  by  $E$ , the non-occurrence of the same event by  $\bar{E}$ . Similarly we have for the occurrence and non-occurrence of other events,  $F, G, H, \dots$  and  $\bar{F}, \bar{G}, \bar{H}, \dots$ .  $E + F$  means that at least one of the two events  $E$  and  $F$  will happen.  $E \times F$  or simply  $E \cdot F$  means the occurrence of both  $E$  and  $F$ . From the above definition it follows immediately that  $\overline{E + F} = \bar{E} \cdot \bar{F}$  and  $E = E \cdot F + E \cdot \bar{F}$ .

This last relation simply states that  $E$  will happen when either  $E$  and  $F$  happen simultaneously or when  $E$  and the non-appearance of  $F$  happen at the same time. If furthermore  $F_1, \bar{F}_1, F_2,$

$\bar{F}_1 \dots F_n, \bar{F}_n$  constitute the members of a complete disjunction, i. e., mutually exclusive events, we have in general:

$$E = E \cdot F_1 + E \cdot \bar{F}_1 + E \cdot F_2 + E \cdot \bar{F}_2 + \dots E \cdot F_n + E \cdot \bar{F}_n.$$

From the original definition of a probability, it follows now:

$$P(E) = P(E \cdot F) + P(E \cdot \bar{F}),$$

and

$$P(E) = P(E \cdot F_1) + P(E \cdot \bar{F}_1) + P(E \cdot F_2) + P(E \cdot \bar{F}_2) \\ + P(E \cdot F_n) + P(E \cdot \bar{F}_n),$$

i. e., the probability that of several mutually exclusive events one at least will happen is the sum of the probabilities of the happening of the separate events. This is the symbolic form for the addition theorem.

**24. Multiplication Theorem.**—We next take two arbitrary events. From these events we may form the following combinations:

$$E \cdot F, E \cdot \bar{F}, \bar{E} \cdot F, \bar{E} \cdot \bar{F}, \text{ i. e.,}$$

Both  $E$  and  $F$  happen,

$E$  happens but not  $F$

$F$  happens but not  $E$

Neither  $E$  nor  $F$  happens.

Furthermore let  $\alpha, \beta, \gamma, \delta$ , be the respective numbers of the favorable cases for the above four combinations of the events  $E$  and  $F$ . Following the previous method of Poincaré, we shall have:

$$P(E) = \frac{\alpha + \beta}{\alpha + \beta + \gamma + \delta}, \quad P(F) = \frac{\alpha + \gamma}{\alpha + \beta + \gamma + \delta},$$

$$P_{\bar{F}}(E) = \frac{\alpha}{\alpha + \gamma}, \quad P_{\bar{E}}(F) = \frac{\alpha}{\alpha + \beta},$$

$$P(E \cdot F) = \frac{\alpha}{\alpha + \beta + \gamma + \delta}.$$

**25. Probability of Repetitions.**—From the above equations it immediately follows:

$$P(E \cdot F) = P(E) \times P_{\bar{E}}(F) = P(F) \times P_{\bar{F}}(E),$$

which is the symbolic form for the multiplication theorems of compound probabilities.

In special cases it may happen that the different subsidiary events:  $E_1, E_2, E_3 \dots E_n$  are all similar. We shall then have, following the symbolic method:

$$E = E_1 \cdot E_2 \cdot E_3 \dots E_n = E_1 \cdot E_1 \cdot E_1 \dots E_1 = E_1^n,$$

and

$$P(E) = P(E_1^n) = P(E_1)^n.$$

This gives us the following theorem:

The probability for the repetition  $n$  times of a certain event,  $E$ , is equal to the  $n$ th power of its absolute probability.

Thus if  $P(E) = p$  we have immediately  $P(\bar{E}) = 1 - p$ .

$$P(E^n) = P(E)^n = p^n.$$

$$P(\bar{E}^n) = P(\bar{E})^n = (1 - p)^n.$$

Thus the probability for the occurrence of  $E$  at least once in  $n$  trials is

$$P(E + E + \dots n \text{ times}) = 1 - P(\bar{E}^n) = 1 - (1 - p)^n.$$

Denoting the numerical quantity of this probability by  $Q$  we have:

$$1 - Q = (1 - p)^n.$$

Solving this equation for  $n$  we shall have:

$$n = \frac{\log(1 - Q)}{\log(1 - p)}.$$

Whenever  $n$  equals, or is greater than, the above logarithmic value for given values of  $Q$  and  $p$  we are sure that  $Q$  will exceed a previously given proper fraction. To illustrate:

*Example 10.*—How often must a die be thrown so that the probability that a six appears at least once is greater than  $\frac{1}{2}$ ?

Here  $p = \frac{1}{6}$ ,  $Q = \frac{1}{2}$ . Hence we must select for  $n$  the smallest positive integer satisfying the relation:

$$\frac{\log(1 - \frac{1}{2})}{\log(1 - \frac{1}{6})} = \frac{\log \frac{1}{2}}{\log \frac{5}{6}} = \frac{.301035}{.079186} \text{ i. e., } n = 4.$$

For this particular value of  $n$  we have in reality:

$$Q = 1 - (\frac{5}{6})^4 = .518.$$

(26.) **Application of the Addition and Multiplication Theorems in Problems in Probabilities.**—We shall next proceed to illustrate the theorems of the preceding paragraphs by a few examples. First, we shall apply the demonstrated theorems to some of the examples we have already solved by a direct application of the fundamental definition of a mathematical probability.

*Example 11.*—We take first of all our old friend, the problem of D’Alambert. What is the probability of throwing head at least once in two successive throws with an uniform coin?

This problem is most easily solved by finding the probability first for not getting head in two successive throws. By the multiplication theorem this probability is:  $p = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ . Then the probability to get head at least once is  $1 - \frac{1}{4} = \frac{3}{4}$  from a simple application of the rule in § 25. A more lengthy analysis is as follows. Denoting the event by  $E$ , the following cases may appear which may bring forth the desired event: Head in first throw which we shall denote by  $H_1$  and head in second throw which we denote by  $H_2$ , or head in first throw ( $H_1$ ) and tail in second ( $T_2$ ), or finally tail in first ( $T_1$ ) and head in second ( $H_2$ ). Then we have:

$$E = H_1 \cdot H_2 + H_1 \cdot T_2 + T_1 \cdot H_2,$$

or:

$$\begin{aligned} P(E) &= P(H_1) \cdot P(H_2) + P(H_1) \cdot P(T_2) + P(T_1) \cdot P(H_2) \\ &= \frac{1}{2} \times \frac{1}{2} + \frac{1}{2} \times \frac{1}{2} + \frac{1}{2} \times \frac{1}{2} = \frac{3}{4}. \end{aligned}$$

27. **Example 12.**—What is the probability of throwing at least twelve in a single throw with three dice? The expected event occurs when either 12, 13, 14, . . . or 18 is thrown. Of these events only one may happen at a time. We may, therefore, apply the addition theorem and obtain as the total probability:

$$p = p_{12} + p_{13} + p_{14} + \cdots + p_{18}.$$

where  $p_{12}, p_{13}, \cdots p_{18}$  are the respective probabilities for throwing the sums of 12, 13, . . . or 18. These subsidiary probabilities were determined in § 13 under the problem of Galileo, and:

$$p = \frac{25}{216} + \frac{31}{216} + \frac{15}{216} + \frac{10}{216} + \frac{6}{216} + \frac{3}{216} + \frac{1}{216} = \frac{91}{216}.$$

28. **Example 13.**—An urn contains  $a$  white,  $b$  black and  $c$  red balls. A single ball is drawn  $\alpha + \beta + \gamma$  times in succession, and the ball thus drawn is replaced before the next drawing takes place. To determine the probability that (1) there are first  $\alpha$  white, then  $\beta$  black and finally  $\gamma$  red balls, (2) the drawn balls appear in three closed groups of  $\alpha$  white,  $\beta$  black and  $\gamma$  red balls, but the order of these groups is arbitrary, (3) that white, black and red balls appear in the same number as above, but in any order whatsoever.

1. Denoting the three subsidiary events for drawing  $\alpha$  white,  $\beta$  black and  $\gamma$  red balls by  $F_1$ ,  $F_2$  and  $F_3$ , and the main event for drawing the balls in the prescribed order by  $E$ , we may write the probability for the occurrence of the main event in following symbolic form involving symbolic probabilities:

$$P(E) = P(F_1)P_{F_1}(F_2)P_{F_1F_2}(F_3).$$

Substituting the algebraic values for  $P(F_1)$ ,  $P(F_2)$  and  $P(F_3)$  in the expression for  $P(E)$ , and then applying Hausdorff's rule (§ 24) we get:

$$\begin{aligned} P(E) = p_1 &= \frac{a^\alpha}{(a+b+c)^\alpha} \times \frac{b^\beta}{(a+b+c)^\beta} \times \frac{c^\gamma}{(a+b+c)^\gamma} \\ &= \frac{a^\alpha b^\beta c^\gamma}{(a+b+c)^{\alpha+\beta+\gamma}}. \end{aligned}$$

2. In the second part of the problem the order of the three different groups is immaterial. The three subsidiary events:  $F_1$ ,  $F_2$  and  $F_3$ , may therefore be arranged in any order whatsoever. The total number of arrangements is  $3! = 6$ . The probability of the happening of any one of these arrangements separately is the same as the probability computed under (1). By applying the addition theorem we get therefore as the probability of the occurrence of this event:

$$p_2 = \frac{6a^\alpha b^\beta c^\gamma}{(a+b+c)^{\alpha+\beta+\gamma}}.$$

3. The third part is more easily solved by a direct application of the definition of a mathematical probability. The order of the balls drawn is here immaterial. Of each individual com-

bination of  $\alpha$  white,  $\beta$  black balls and  $\gamma$  red balls it is possible to form  $(\alpha + \beta + \gamma)!/\alpha!\beta!\gamma!$  different permutations as the total number of favorable cases. The above number of equally possible cases is here  $(a + b + c)^{\alpha+\beta+\gamma}$ . Hence we have:

$$p_1 = \frac{(\alpha + \beta + \gamma)!}{\alpha!\beta!\gamma!} \times \frac{a^\alpha b^\beta c^\gamma}{(a + b + c)^{\alpha+\beta+\gamma}}.$$

29. **Example 14.**—In an urn are  $n$  balls among which are  $\alpha$  white and  $\beta$  black. What is the probability in three successive drawings to draw (1) first two white and then one black ball, (2) two white and one black ball in any order whatsoever? ( $\alpha + \beta \leq n$ ). The probability to draw first one white, then another white and finally a black ball is:

$$p_1 = \frac{\alpha}{n} \frac{(\alpha - 1)}{(n - 1)} \times \frac{\beta}{(n - 2)}.$$

The probability for any of the other arrangements is the same, or we have for (2)

$$p_2 = 3p_1 = \frac{3\alpha}{n} \frac{(\alpha - 1)}{(n - 1)} \times \frac{\beta}{(n - 2)}.$$

30. **Example 15.**—What is the chance to throw a doublet of 6 at least once in  $n$  consecutive throws with two dice? (Pascal's Problem.)

Chevalier de Mere, a French nobleman and a great friend of all games of chance, went more deeply into the complex of causes in different games than most of the ordinary gamblers of his time. Although not a proficient mathematician he understood sufficient, nevertheless, to give some very interesting problems for which he got the ideas from the gambling resorts he frequented. De Mere was a friend of the great French mathematician and philosopher, Blaise Pascal, and went to him whenever he wanted information on some apparently obscure point in the different games in which he participated. The chevalier had from patient observation noticed that he could profitably bet to throw a six at least once in four throws with a single die. He reasoned now that the number of throws to throw a doublet at least once with two dice ought to be proportional to the corresponding equal number of possible cases with a single die. For one die there are

6 possible cases, for two 36. Thus de Mere thought he could safely bet to throw a doublet of 6 in 24 throws with two dice. An actual trial by several games of dice proved extremely disastrous to the finances of the nobleman, who then went to Pascal for an explanation. Pascal solved the problem by a direct application of the definition of a mathematical probability. We shall, however, solve it by an application of the multiplication theorem.

The probability to get a doublet of 6 in a single throw is  $\frac{1}{36}$ . The probability of not getting a double six is therefore  $1 - \frac{1}{36} = \frac{35}{36}$ . The probability of the happening of this event  $n$  consecutive times is  $(\frac{35}{36})^n$ . Thus the probability of getting a double six at least once in  $n$  throws with two dice becomes:  $p = 1 - (\frac{35}{36})^n$ . Solving this equation for  $n$  we shall have:

$$n = \frac{\log(1 - p)}{\log 35 - \log 36},$$

for  $p = \frac{1}{2}$  we shall have:

$$n = \frac{\log 2}{\log 36 - \log 35} = 24.6 \dots$$

First for 25 throws we may bet safely one to one while for 24 throws such a bet was unfavorable. This shows the fallacy of de Mere's reasoning.

**31. Example 16.**—An urn,  $A$ , contains  $a$  balls of which  $\alpha$  are white, another similar urn,  $B$ , contains  $b$  balls of which  $\beta$  are white. A single ball is drawn from one of the two urns. What is the probability that the ball is white? The beginner may easily make the following error in the solution of this problem. The probability to get a white ball from  $A$  is  $\alpha/a$ , from  $B$ ,  $\beta/b$ . Thus the total probability to get a white ball is:  $\alpha/a + \beta/b$ . This result is, however, wrong, for we may, by selecting proper values for  $a$ ,  $b$ ,  $\alpha$  and  $\beta$ , obtain a total probability which in numerical value is greater than unity. Thus if  $a = 7$ ,  $b = 7$ ,  $\alpha = 5$ ,  $\beta = 4$ , we get as the total probability:

$$p = \frac{5}{7} + \frac{4}{7} = \frac{9}{7}.$$

This result is evidently wrong, since a mathematical probability is never an improper fraction. The error lies in the fact that we

have regarded the two events of drawing a ball from either urn as independent and mutually exclusive. A simple application of the symbolic rule for relative probabilities will give us the result immediately. The main event,  $E$ , is composed of the two following subsidiary events: (1) to get a white ball from  $A$ , or (2) to get a white ball from  $B$ . We shall symbolically denote these two events by  $A \cdot W$  and  $B \cdot W$  respectively. Thus we have:

$$P(E) = P(A \cdot W) + P(B \cdot W) = P(A)P_A(W) + P(B)P_B(W).$$

Now the probability to obtain urn  $A$  is  $P(A) = p_1 = \frac{1}{2}$ , also to get  $B$ :  $P(B) = p_2 = \frac{1}{2}$ . The probability to get a white ball from  $A$  when this particular urn is previously selected is expressed by the relative probability:

$$P_A(W) = p_3 = \frac{\alpha}{a}.$$

Similarly for  $B$ :

$$P_B(W) = p_4 = \frac{\beta}{b}.$$

Substituting these different values in the expression for  $P(E)$  we get finally:

$$P(E) = p = \frac{1}{2} \times \frac{\alpha}{a} + \frac{1}{2} \times \frac{\beta}{b} = \frac{1}{2} \left( \frac{\alpha}{a} + \frac{\beta}{b} \right).$$

For the particular numerical example we have:

$$p = \frac{1}{2} \left( \frac{5}{7} + \frac{4}{7} \right) = \frac{9}{14}.$$

**32. Example 17.**—The probability of the happening of a certain event,  $E$ , is  $p$ , while the probability for the non-occurrence of the same event is  $q = 1 - p$ . The trial is now to be repeated  $n$  times. The probability that there will be first  $\alpha$  successes and then  $\beta$  failures is:

$$P(E^\alpha)P_{\bar{E}}(\bar{E}^\beta) = p^\alpha \cdot q^\beta (\alpha + \beta = n).$$

This is the probability that the two complementary events  $E$  and  $\bar{E}$  happen in the order prescribed above. When the order, in which the successes and failures happen, plays no rôle during the  $n$  trials, that is to say it is only required to obtain  $\alpha$  successes

and  $\beta$  failures in any order whatsoever in  $n$  total trials, then the arrangement of the  $\alpha$  factors  $p$  and  $\beta$  factors  $q$  is immaterial. The total number of arrangements of  $n$  elements of which  $\alpha$  are equal to  $p$  and  $\beta$  equal to  $q$  is simply  $n!/(\alpha! \times \beta!)$ . For any one particular arrangement of  $\alpha$  factors  $p$  and  $\beta$  factors  $q$  the probability of the happening of the two complementary events in this particular arrangement is equal to  $p^\alpha \cdot q^\beta$ . The Addition Theorem immediately gives the answer for  $\alpha$  successes and  $\beta$  failures in any order whatsoever as:

$$P(E^\alpha \cdot \bar{E}^\beta) = p_\alpha = \binom{n}{\alpha} p^\alpha q^{n-\alpha}.$$

Let us, for the present, regard this probability as being a function of the variable quantity,  $\alpha$ , ( $n$  being a constant quantity). We may then write:

$$p_\alpha = \varphi(\alpha).$$

Letting  $\alpha$  assume all positive integral values from 0 to  $n$  the above expression for  $p_\alpha$  becomes:

$$\begin{aligned} p_0 &= \binom{n}{0} p^0 \cdot q^n, & p_1 &= \binom{n}{1} p \cdot q^{n-1}, \\ p_2 &= \binom{n}{2} p^2 \cdot q^{n-2}, & \dots & p_n = p^n. \end{aligned}$$

These are the respective probabilities for no successes, one success, two successes, . . . and finally  $n$  successes in  $n$  trials. The above quantities are, however, merely the different members of the binomial expansion  $(p + q)^n$ . Since  $p + q = 1$  from the nature of the problem, we also have  $(p + q)^n = 1$ , or  $p_0 + p_1 + p_2 + \dots + p_n = 1$ . This last equation is the symbolic form for the simple hypothetical disjunctive judgment:  $E$  must happen either 0, 1, 2, . . . or  $n$  times in  $n$  total trials. We shall return to this problem later under the discussion of the Bernoullian Theorem. In fact, the above example constitutes an essential part of this famous theorem which has proven one of the most important and far reaching in the whole theory of probability.

**33. Example 18. De Moivre's Problem.**—The following problem was first given by the eminent French-English mathemati-

cian, Abraham de Moivre, in a treatise, entitled "De Mensura Sortis," which was published in London about 1711.

An urn contains  $n + 1$  balls marked  $0, 1, 2, \dots n$ . A person makes  $i$  drawings in succession, and each ball is put back in the urn before the next drawing takes place. What is the probability that the sum of the numbers on the  $n$  balls thus drawn equals  $s$ ?

The first ball may be drawn in  $n + 1$  ways, the second ball may also be drawn in  $n + 1$  ways. Hence two balls may be drawn in  $(n + 1)^2$  ways or  $i$  balls in  $(n + 1)^i$  ways: This is the total number of equally possible cases.

If we expand the expression:

$$(x^0 + x^1 + x^2 + x^3 + x^4 + \dots x^n)^i \quad (1)$$

after the multinomial theorem, we notice that the coefficient to  $x^s$  arises out of the different ways in which  $0, 1, 2, 3, \dots n$  can be grouped together so as to form  $s$  by addition, which also is the total number of favorable cases. The expression (1) inside the bracket represents a geometrical progression, which may be written as:

$$(1 - x^{n+1})^i (1 - x)^{-i} = \left\{ 1 - ix^{n+1} + \binom{i}{2} x^{2n+2} - \binom{i}{3} x^{3n+3} + \dots \right\} \times \left\{ 1 + ix + \binom{i+1}{2} x^2 + \binom{i+2}{3} x^3 + \dots \right\}.$$

By actual multiplication we get a power series in  $x$ . The terms containing  $x^s$  are obtained in the following manner: the first term of the first factor being multiplied with the term

$$\binom{i+s-1}{s} x^s \text{ of the second factor,}$$

the second term of the first factor multiplied with the term:

$$\binom{i+s-n-2}{s-n-1} x^{s-n-1} \text{ of the second factor,}$$

the third term of the first factor multiplied with the term:

$$\binom{i+s-2n-3}{s-2n-2} x^{s-2n-2} \text{ of the second factor.}$$

. . . . .

Thus the coefficient of  $x^i$  is equal to

$$\binom{i+s-1}{s} - \binom{i}{1} \binom{i+s-n-2}{s-n-1} \\ + \binom{i}{2} \binom{i+s-2n-3}{s-2n-2} - \dots$$

The above expression may by further reductions be brought to the form:

$$\frac{(s+1)(s+2) \dots (s+i-1)}{1 \cdot 2 \dots (i-1)} \\ - \binom{i}{1} \frac{(s-n)(s-n+1) \dots (s-n+i-2)}{1 \cdot 2 \dots (i-1)} \\ + \binom{i}{2} \frac{(s-2n-1)(s-2n) \dots (s-2n+i-3)}{1 \cdot 2 \dots (i-1)} - \dots$$

The series breaks of course as soon as negative factors appear in the numerator. The required probability is therefore

$$P_s = \frac{1}{(n+1)^i} \left\{ \frac{(s+1)(s+2) \dots (s+i-1)}{1 \cdot 2 \dots (i-1)} \right. \\ \left. - \binom{i}{1} \frac{(s-n)(s-n+1) \dots (s-n+i-2)}{1 \cdot 2 \dots (i-1)} + \dots \right\}.$$

**34. Example 19.**—If a single experiment or observation is made on  $n$  pairs of opposite (complementary) events,  $E_\alpha$  and  $\bar{E}_\alpha$  with the respective probabilities of happening  $p_\alpha$  and  $q_\alpha$  ( $\alpha = 1, 2, 3, \dots, n$ ), to determine the probability that: (1) exactly  $r$ , (2) at least  $r$  of the events  $E_\alpha$  will happen.

This problem is of great importance, especially in life assurance mathematics. It happens frequently that an actuary is called upon to determine the probability that exactly  $r$  persons will be alive  $m$  years from now out of a group of  $n$  persons of any age whatsoever, each person's age and his individual coefficient of survival through the period being known beforehand.

Various demonstrations have been given of this problem. The first elementary proof was probably due to Mr. George King,

the English actuary, in his well-known text-book. The Austrian mathematician and actuary, E. Czuber, has simplified King's method in his "Wahrscheinlichkeitsrechnung" (1903). Later the Italian actuary, Toja, has given an elegant proof in *Bolletino degli Attuari*, Vol. 12. Finally another Italian mathematician, P. Medolaghi, has investigated the problem from the standpoint of symbolic logic. In the following we shall adhere to the demonstration of Czuber and also give a short outline of the symbolic method.

In order to answer the first part of the problem we must form all possible combinations of  $r$  factors of  $p$  and  $n - r$  factors of  $q$  and then sum all such combinations of  $n$  factors. Denoting the event by  $E_{[r]}$  we have:

$$\begin{aligned} P(E_{[r]}) &= \Sigma p_1 p_2 p_3 \cdots q_n q_{n-1} \cdots q_r \\ &= \Sigma p_1 p_2 \cdots (1 - p_n)(1 - p_{n-1}) \cdots (1 - p_r). \end{aligned} \quad (1)$$

We shall now denote the *sum* of all products in (1) containing  $\varphi$  factors  $p$  by the symbol  $S_\varphi$ . It is readily seen that  $\varphi$  will have all positive integral values from  $r$  to  $n$  inclusive. We may therefore write the total compound probability in the following form:

$$P(E_{[r]}) = A_0 S_r + A_1 S_{r+1} + A_2 S_{r+2} + \cdots + A_{n-r} S_n. \quad (2)$$

The student must bear in mind that the different  $S$  are merely symbols for different *sums* of all the products of  $r, r + 1, r + 2, \cdots n$  factors  $p$  respectively. Our problem is now to determine the unknown coefficients  $A$ . It is easily seen that the coefficient  $A_0 = 1$ , since all different products containing  $r$  factors  $p$  appear only once. The other coefficients of the form  $A$  do not depend on the values of  $p$ , however. They remain therefore unaltered if we equate all of the various  $p$ 's and let them equal  $p$ . Expression (1) then simply becomes  $\binom{n}{r} \cdot p^r (1 - p)^{n-r}$ . We must form all possible  $r$ th powers of  $n$  similar factors, which can be done in  $\binom{n}{r}$  ways. The expression (2) on the other hand

becomes:

$$\binom{n}{r} \cdot p^r + A_1 \binom{n}{r+1} \cdot p^{r+1} + A_2 \binom{n}{r+2} \cdot p^{r+2} + \dots + A_{n-r} p^n.$$

Any  $S_\varphi$  is by definition the sum of all products containing  $\varphi$  factors  $p$  and we may form  $\binom{n}{\varphi}$  such products from  $n$  elements  $p$ . But we saw above that  $\varphi$  might only have all positive values from  $r$  to  $n$  inclusive, hence expression (2) will naturally take the above form. We have therefore

$$\begin{aligned} \binom{n}{r} \cdot p^r (1-p)^{n-r} &= \binom{n}{r} \cdot p^r + A_1 \binom{n}{r+1} p^{r+1} \\ &\quad + A_2 \binom{n}{r+2} \cdot p^{r+2} + \dots + A_{n-r} p^n. \end{aligned}$$

Expanding the expression on the left hand side by means of the binomial theorem and equating the coefficients of equal powers of  $p$ , we get:

$$\begin{aligned} -\binom{n}{r} \binom{n-r}{1} &= A_1 \binom{n}{r+1}; \quad \binom{n}{r} \binom{n-r}{2} = A_2 \binom{n}{r+2} \\ -\binom{n}{r} \binom{n-r}{3} &= A_3 \binom{n}{r+3}, \quad \dots \quad (-1)^{n-r} \binom{n}{r} \binom{n-r}{n-r} = A_{n-r}, \end{aligned}$$

or:

$$\begin{aligned} A_1 &= -\binom{r+1}{1}, \quad A_2 = \binom{r+2}{2}, \quad A_3 = -\binom{r+3}{3}, \quad \dots \\ A_{n-r} &= (-1)^{n-r} \binom{n}{n-r}. \end{aligned}$$

Substituting these values in (2) for the unknown coefficients  $A$ , we shall have:

$$\begin{aligned} P(E_{[r]}) &= S_r - \binom{r+1}{1} S_{r+1} + \binom{r+2}{2} S_{r+2} - \dots \\ &\quad + (-1)^{n-r} \binom{n}{n-r} S_n. \end{aligned}$$

If we expand the algebraic expression:

$$\frac{S^r}{(1+S)^{r+1}} = S^r(1+S)^{-(r+1)}$$

we have:

$$S^r - \binom{r+1}{1} S^{r+1} + \binom{r+2}{2} S^{r+2} - \dots \\ + (-1)^{n-r} \binom{n}{n-r} S^n - \dots$$

We may therefore write  $P(E) = \frac{S^r}{(1+S)^{r+1}}$ , when every expo-

nent is replaced by an index number (*i. e.*,  $S^k$  replaced by  $S_k$ ) and the expansion broken off at the term  $S^n$ . The student must of course constantly bear in mind the symbolic meaning of  $S_k$ .

The second part of the problem is easily solved by the symbolic method. Denoting this particular event by  $E_r$ , we have the following identity:

$$P(E_r) - P(E_{r+1}) = P(E_{r1})$$

or

$$P(E_r) - P(E_{r1}) = P(E_{r+1}).$$

The following relations are self-evident:

$$P(E_0) = 1;$$

$$P(E_{10}) = \frac{S^0}{1+S} = \frac{1}{1+S};$$

$$P(E_1) = P(E_0) - P(E_{10}) = 1 - \frac{1}{1+S}, \text{ also;}$$

$$P(E_2) = P(E_1) - P(E_{11}) = \frac{S}{1+S} - \frac{S}{(1+S)^2} = \frac{S^2}{(1+S)^2}.$$

The complete induction gives us finally:

$$P(E_r) = \frac{S^r}{(1+S)^{r+1}}.$$

Assuming the rule is true for  $r$ , we may easily prove it is true for  $r+1$  also. We have in fact:

$$\frac{S^r}{(1+S)^r} - \frac{S^r}{(1+S)^{r+1}} = \frac{S^{r+1}}{(1+S)^{r+1}}.$$

**35. Example 20. Tchebycheff's Problem.**—The following solution of a very interesting problem is due to the eminent Russian mathematician, Tchebycheff, one of the foremost of modern analysts.

A proper fraction is chosen at random. What is the probability it is in its lowest terms?

Stated in a slightly different wording the same question may also be put as follows: If  $A/B$  is a proper fraction, what is the probability that  $A$  and  $B$  are prime to each other?

If  $p_2, p_3, p_5, \dots, p_m$  denote respectively the probabilities that each of the primes 2, 3, 5,  $\dots, m$  is *not* a common factor of numerator and denominator of  $A/B$ , then the probability that *no* prime number is a common factor is:

$$P = p_2 \cdot p_3 \cdot p_5 \cdots p_m \cdots \text{ad. inf.} \quad (\text{I})$$

This follows from the multiplication theorem and from the fact that the sequence of prime numbers is infinite.

Tchebycheff now first finds the probability  $q_m = 1 - p_m$  that the fraction  $A/B$  *does* contain the prime  $m$  as factor of both  $A$  and  $B$ . By dividing any integral number by the prime  $m$  we obtain besides the quotient a certain remainder that must be one of the following numbers, viz.:

$$0, 1, 2, 3, 4, \dots (m-1).$$

Each of the above remainders may be regarded as a possible event. The probability to obtain 0 as a remainder is accordingly  $1/m$ . The probability that  $m$  is contained as a factor of  $A$  is therefore  $1/m$ . This same quantity is also the probability that  $m$  is a factor of  $B$ . The probability that both  $A$  and  $B$  are divisible by  $m$  is therefore:

$$q_m = 1 - p_m = \frac{1}{m} \cdot \frac{1}{m} = \frac{1}{m^2}, \quad \text{or} \quad p_m = 1 - \frac{1}{m^2}.$$

Hence we have for the various primes:

$$p_2 = 1 - \frac{1}{2^2}, \quad p_3 = 1 - \frac{1}{3^2}, \quad p_5 = 1 - \frac{1}{5^2}, \quad \dots.$$

Formula (I) then takes the form:

$$P = \left(1 - \frac{1}{2^2}\right) \left(1 - \frac{1}{3^2}\right) \left(1 - \frac{1}{5^2}\right) \cdots \text{ad. inf.} \quad (\text{II})$$

Forming the reciprocal  $1/P$  we get:

$$\frac{1}{P} = \frac{1}{1 - \frac{1}{2^2}} \cdot \frac{1}{1 - \frac{1}{3^2}} \cdot \frac{1}{1 - \frac{1}{5^2}} \cdots \text{ad. inf.}$$

Now each factor on the right hand side is the sum of a geometrical progression, as:

$$\begin{aligned} \frac{1}{P} = & \left(1 + \frac{1}{2^2} + \frac{1}{(2^2)^2} + \cdots\right) \left(1 + \frac{1}{3^2} + \frac{1}{(3^2)^2} + \cdots\right) \\ & \left(1 + \frac{1}{5^2} + \frac{1}{(5^2)^2} + \cdots\right) \cdots \text{ad. inf.} \end{aligned}$$

Multiplying out we shall have:

$$\frac{1}{P} = \frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \frac{1}{5^2} + \cdots \text{ad. inf.}$$

The above infinite series is, however, merely the well known Eulerian expression for  $\pi^2/6$ , hence:

$$P = \frac{6}{\pi^2}.$$

Suppose furthermore we were assured that none of the three primes 2, 3, 5 was a common factor of both  $A$  and  $B$ . What would then be the probability that the fraction might be reduced by division by one or more of the other primes?

Denoting by the symbol  $P_{(7)}$  the probability that *none* of the primes from 7 and upwards is a common factor, we get:

$$P_{(7)} = \left(1 - \frac{1}{7^2}\right) \left(1 - \frac{1}{11^2}\right) \left(1 - \frac{1}{13^2}\right) \cdots \text{ad. inf.},$$

also:

$$P = \frac{6}{\pi^2} = \left(1 - \frac{1}{2^2}\right) \left(1 - \frac{1}{3^2}\right) \left(1 - \frac{1}{5^2}\right) P_{(7)},$$

or:

$$P_m = \frac{6}{\pi^2} \div \left[ \left(1 - \frac{1}{2^2}\right) \left(1 - \frac{1}{3^2}\right) \left(1 - \frac{1}{5^2}\right) \right] = 0.950.$$

The probability of the divisibility of both numerator and denominator of a fraction chosen at random by a prime larger than 5 is thus:

$$1 - P_m = \frac{1}{20}.$$

The summation of the infinite series of the reciprocals of the squares of the natural numbers baffled for a long time the skill of some of the most eminent mathematicians. Jacob Bernoulli, the renowned classical writer on probabilities, proved its convergence but failed to find its sum. The final summation was first performed by Euler.

## CHAPTER V.

3

### MATHEMATICAL EXPECTATION.

**36. Definition, Mean Values.**—It is common belief among many people that gambling and all kinds of betting have their source in reckless desire. This is often argued by moral reformers, but cannot be said to be the true cause. Whenever by ordinary gambling or by a bet, actual value is exposed to a complete or partial loss, this exposure is not due to the fact that the gamester is reckless, but because there is hope of an actual gain. "Hope," says Spinoza in his treatise on ethics, "is the indeterminate joy caused by the conception of a future state of affairs of whose outcome we are in doubt." Actual mathematical calculation cannot be attempted on the basis of this definition any more than it could be attempted to determine a mathematical probability from the definition of Aristotle. "We disregard therefore the psychological element of desire, which is associated with hope or expectation as well as the anxiousness or dread associated with the related psychological element of non-desire" (Cantor).

The so-called *mathematical expectation* is the product of an expected gain in actual value and the mathematical probability of obtaining such a gain. The danger of loss may in this case be regarded as a negative gain. Thus if a person,  $A$ , may expect the gain,  $G$ , from the event,  $E$ , whose probability of happening is equal to  $p$ , then  $e = p \cdot G$  is his mathematical expectation. The quantity expressed by the symbol,  $e$ , is here the amount it is safe to hazard for the expected gain,  $G$ . We may also regard the quantity,  $e$ , as a mean value or average value. Among a large number of  $n$  cases only  $np$  will bring the gain,  $G$ , the others not. Thus the total gain is:

$$pnG \div n = pG.$$

Suppose we have  $n$  mutually exclusive events,  $E_1, E_2, \dots, E_n$ .

forming a complete disjunction. For their respective probabilities we have then the following equation:

$$p_1 + p_2 + p_3 + \cdots + p_n = 1.$$

If the actual occurrence of a certain one of these events, say,  $E_\alpha$ , brings a gain of  $G_\alpha$ , then the total value of the mathematical expectation of the  $n$  events is:

$$e = p_1 \cdot G_1 + p_2 \cdot G_2 + \cdots + p_n \cdot G_n = \Sigma p_\alpha \cdot G_\alpha.$$

Since  $\Sigma p_\alpha = 1$  this result may be written:

$$e \times (p_1 + p_2 + \cdots + p_n) = G_1 \cdot p_1 + G_2 \cdot p_2 + G_3 \cdot p_3 + \cdots G_n \cdot p_n,$$

hence  $e$  may be regarded as the mean value of the different quantities  $G_\alpha$  with the weights  $p_\alpha$  ( $\alpha = 1, 2, 3, \cdots, n$ ).

Although we shall discuss the theory of mean values in a following chapter a few preliminary remarks might not be out of place here.

A variable quantity  $X$  is related to a series of events  $E_1, E_2, E_3, \cdots, E_n$  (it being assumed that these events form a complete disjunction) in such a manner that when  $E_\alpha$  happens  $X$  takes on the value  $x_\alpha$  ( $\alpha = 1, 2, 3, \cdots, n$ ). If furthermore  $p_1, p_2, p_3, \cdots$  denote the respective probabilities of the occurrence of  $E_1, E_2, E_3, \cdots$ , then

$$M(X) = p_1 x_1 + p_2 x_2 + \cdots p_n x_n$$

is called the mean value or simply the mean of  $X$ .

The above definition may be illustrated by the following concrete urn-scheme. An urn contains  $N$  balls of which  $a_1$  balls are marked  $x_1$ ,  $a_2$  balls marked  $x_2$   $\cdots$  and finally  $a_n$  balls marked  $x_n$  where  $a_1 + a_2 + a_3 + \cdots + a_n = N$ . Each drawing from the urn produces a certain number  $X$ , which may assume  $n$  different values  $x_1, x_2, x_3, \cdots, x_n$ , each with the respective probabilities:

$$p_1 = \frac{a_1}{N}, p_2 = \frac{a_2}{N} \cdots p_n = \frac{a_n}{N}.$$

The arithmetic mean of all the numbers written on the balls is:

$$\frac{a_1 x_1 + a_2 x_2 + \cdots a_n x_n}{N},$$

which agrees with the mean as defined above.

**37. The Petrograd (St. Petersburg) Problem.**—In this connection it is worthy to note a celebrated problem, which on account of its paradoxical nature has become a veritable stumbling block, and has been discussed by some of the most eminent writers on probabilities. The problem was first suggested by Daniel Bernoulli in a communication to the Petrograd—or as it was then called St. Petersburg Academy—in 1738.

The Petrograd problem may shortly be stated as follows: Two persons *A* and *B* are interested in a game of tossing a coin under the following conditions. An ordinary coin is tossed until head turns up, which is the deciding event. If head turns up the first time *A* pays one dollar to *B*, if head appears first at the second toss *B* is to receive two dollars, if first at the third time four dollars and so on. What is the mathematical expectation of *B*? Or in other words, how much must *B* pay to *A* before the game starts in order that the game may be considered fair?

The mathematical expectation of *B* in the first trial is  $\frac{1}{2} \times 1 = \frac{1}{2}$ . The mathematical expectation for head in second throw is  $(\frac{1}{2})^2 \times 2 = \frac{1}{2}$ . Or in general the mathematical probability that head appears for the first time in the *n*th toss is  $(\frac{1}{2})^n$ , and the co-ordinated expectation is  $2^{n-1} \div 2^n = \frac{1}{2}$ . Thus the total expectation is expressed by the following series:

$$\frac{1}{2} + \frac{1}{2} + \frac{1}{2} + \dots$$

When  $n = \infty$  as its limiting value it thus appears that *B* could afford to pay an infinite amount of money for his expected gain.

**38. Various Explanations of the Paradox. The Moral Expectation.**—This evidently paradoxical result has called forth a number of explanations of various forms by some eminent mathematicians. One of the commentators was D’Alambert. It was to be expected that the famous encyclopædist, who—as we have seen—did not view the theory of probabilities in too kindly a manner, would not hesitate to attack. He returns repeatedly to this problem in the “Opuscules” (1761) and in “Doutes et questions” (Amsterdam, 1770).

D’Alambert distinguishes between two forms of possibilities, viz., metaphysical and physical possibilities. An event is by

him called a metaphysical possibility, when it is not absurd. When the event is not too "uncommon" in the ordinary course of happenings it is a physical possibility. That head would appear for the first time after 1,000 throws is metaphysically possible but quite impossible physically. This contention is rather bold. "What would," as Czuber remarks, "D'Alambert have said to an actual reported case in 'Grunert's Archiv' where in a game of whist each of the four players held 13 cards of one suit." The numerical probability of such an event as expressed by mathematical probabilities is  $(635013559600)^{-4}$ .

D'Alambert's definitions including the half metaphorical term "ordinary course" are rather vague. And what numerical value of the mathematical probability constitutes the physical impossibility? D'Alambert gives three arbitrary solutions for the probability of getting head in the  $n$ th throw, namely:

$$\frac{1}{2^n(1 + \beta n^2)}, \quad \frac{1}{2^{n+\alpha n}}, \quad \frac{1}{2^n + \frac{2^n B}{(K-n)^{q/2}}},$$

where  $\alpha, \beta, B, K$  are constants and  $q$  an uneven number.

Daniel Bernoulli himself gives a solution wherein he introduces the term "moral expectation." If a person possesses a sum of money equal to  $x$  then according to Bernoulli

$$dy = \frac{kdx}{x}$$

is the moral expectation of  $x$ ,  $k$  being a constant quantity. Integrating we get:

$$\int_a^b dy = k \int_a^b \frac{dx}{x} = k(\log b - \log a) = k \log \frac{b}{a},$$

which is the moral expectation of an increase  $b - a$  of an original value  $a$ . If now  $x$  denotes the sum owned by  $B$  we may replace the mathematical expectation by their corresponding moral expectations, that is to say replace  $2^{n-1}/2^n$  by  $(1/2^n) \log ((x + 2^{n-1})/x)$  and we then have:

$$k \left( \frac{1}{2} \log \frac{x+1}{x} + \frac{1}{4} \log \frac{x+2}{x} + \dots + \frac{1}{2^n} \log \frac{x+2^n}{x} \right),$$

which is a convergent series. In this connection, it may be mentioned that the Bernoullian hypothesis has found quite an extensive use in the modern theory of utility.

De Morgan in his splendid little treatise "On Probabilities" takes the view that the solution as first given is by no means an anomaly. He quotes an actual experiment in coin tossing by Buffon. Out of 2,048 trials 1,061 gave head at the first toss, 494 at the second, 232 at the third, 137 at the fourth, 56 at the fifth, 29 at the sixth, 25 at the seventh, 8 at the eighth and 6 at the ninth. Computing the various mathematical expectations, we find that the maximum value is found in the 25 sets with head in the seventh toss, which gives a gain of  $25 \times 64 = 1,600$ . The most rare occurrence, the 6 sets of head in the ninth throw gives a gain of  $6 \times 256 = 1,536$ , which is the next highest gain in all the nine sets. De Morgan furthermore contends that if Buffon had tried a thousand times as many games, the results would not only have given more, but *more per game*, arguing "that a larger net would have caught not only more fish but more varieties of fish; and in two millions of sets, we might have seen cases in which head did not appear till the twentieth throw." Furthermore, "the player might continue until he had realized not only any given sum, but any given sum per game." Therefore according to De Morgan the mathematical expectation of a player in a single game must be infinite.

## CHAPTER VI.

0

### PROBABILITY A POSTERIORI.

**39. Bayes's Rule. A Posteriori Probabilities.**—The problems hitherto considered have all had certain points in common. Before entering upon the calculations of the mathematical probability of the happening of the event in question, we knew beforehand a certain complex of causes which operated in the general domain of action. We also were able to separate this general complex of productive causes into two distinctive minor domains of complexes, of which one would bring forth the event,  $E$ , while the other domain would act towards the production of the opposite event,  $\bar{E}$ . Furthermore we also were able to measure the respective quantitative magnitudes of the two domains, and then, by a simple algebraic operation, determine the probability as a proper fraction. The addition and multiplication theorems did not introduce any new principles, but only gave us a set of systematic rules which facilitated and shortened the calculations of the relations between the different absolute probabilities. The above method of determination of a mathematical probability is known as an a priori determination, and such probabilities are termed a priori probabilities.

The problems treated in the preceding chapters have, nearly all, been related to different games of chance, or purely abstract mathematical quantities. The inorganic nature of this kind of problems has made it possible for us to treat them in a relatively simple manner. In many of the problems, which we shall consider hereafter, organic elements enter as a dominant factor and make the analysis much more complicated and difficult.

All social and biological investigations, which are of a much larger benefit and practical value than the problems in games of chance, lead often to a completely different category of probability problems, which are known as "a posteriori probabilities." In problems where organic life enters into the calculations, the complex of productive causes is so varied and manifold, that

our minds are not able to pigeonhole the different productive causes, placing them in their proper domains of action. But we know that such causes do exist and are the origin of the event. If now, by a series of observations, we have noticed the actual occurrence of the event,  $E$  (or the occurrence of the opposite event  $\bar{E}$ ), the problem of the determination of an a posteriori probability to find the probability that the event  $E$  originated from a certain complex, say  $F$ . We must then, first of all, form a complete hypothetical judgment of the form:  $E$  either happens from the complexes  $F_1$ , or  $F_2$ , or  $F_3$ ,  $\dots$  or  $F_n$ . But we must not forget that, in general, the different complexes  $F_\alpha$  ( $\alpha = 1, 2, \dots, n$ ) of the disjunction are not known a priori. We must, therefore, determine the respective probabilities for the actual existence of such disjunctive complexes  $F_\alpha$ . These probabilities of existence for the complexes of causes are in general different for each member, a fact which often has been overlooked by many investigators and writers on a posteriori probabilities, and which has given rise to meaningless and paradoxical results.

**40. Discovery and History of the Rule.**—The first discoverer of the rule for the computation of a posteriori probabilities by a purely deductive process was the English clergyman, T. Bayes. Bayes's treatise was first published after the death of the author by his friend, Dr. Price, in *Philosophical Transactions* for 1763. The treatise by the English clergyman was, for a long time, almost forgotten, even by the author's own countrymen; and later English writers have lost sight of the true "Bayes's Rule" and substituted a false, or to be more accurate, a special case of the exact rule, in the different algebraic texts, under the discussion of the so called "inverse probabilities," a name which is due probably to de Morgan, and which in itself is a great misnomer. This point, presently, we shall discuss in detail.

The careless application of the exact rule has recently led to a certain distrust of the whole theory of "a posteriori probabilities." Scandinavian mathematicians were probably the first to criticize the theory. In 1879, Mr. J. Bing, a Danish actuary, took a very critical attitude towards the mathematical principles underlying Bayes's Rule, in a scholarly article in the *mathe-*

mathematical journal *Tidsskrift for Matematik*. Bing's article caused a sharp, and often heated, discussion among the older and younger Danish mathematicians at that time; but his views seem to have gained the upper hand, and even so great an authority on the whole subject as the late Dr. T. Thiele, in his well-known work, "Theory of Observations" (London, 1903), refers to Bing's article as "a crushing proof of the fallacies underlying the determination of a posteriori probabilities by a purely deductive method." As recently as 1908, the Danish writer on philosophy, Dr. Kroman, has taken up cudgels in defense of Bayes in a contribution in the *Transactions of the Royal Danish Academy of Science*, which has done much towards the removal of many obscure and erroneous views of the older authors. Among English writers, Professor Chrystal, in a lecture delivered before the Actuarial Society of Edinburgh, has also given a sharp criticism of the rule, although he does not go so deeply into the real nature of the problem as either Bing or Kroman.

Despite Chrystal's advice to "bury the laws of inverse probabilities decently out of sight, and not embalm them in text books and examination papers" the old view still holds sway in recent professional examination papers. It is therefore absolutely necessary for the student preparing for professional examinations to be acquainted with the theory. In the following paragraphs we shall, therefore, give the mathematical theory of Bayes's Rule with several examples illustrating its application to actual problems, together with a criticism of the rule.

41. Bayes's Rule (Case I).—(*The different complexes of causes producing the observed event,  $E$ , possess different a priori probabilities of existence.*) Let  $E$  denote a certain state or condition, which can appear under only one of the mutually exclusive complexes of causes:  $F_1, F_2, \dots$  and not otherwise. Let the probability for the actual existence of  $F_1$  be  $\kappa_1$  and if  $F_1$  really exists then let  $\omega_1$  be the "productive probability" for bringing forth the observed event,  $E$  ( $E$  being of a different nature from  $F$ ), which can only occur after the previous existence of one of the mutually exclusive complexes,  $F$ . Let, in the same manner,  $F_2$  have an "existence probability" of  $\kappa_2$  and a "productive probability" of  $\omega_2$ ,  $F_3$  an existence probability of  $\kappa_3$  and a pro-

ductive probability of  $\omega_1 \dots$  etc. If now, by actual observation, we have noted that the event  $E$  has occurred exactly  $m$  times in  $n$  trials, then the probability that the complex  $F_1$  was the origin of  $E$  is:

$$Q_1 = \frac{\kappa_1 \cdot \omega_1^m (1 - \omega_1)^{n-m}}{\sum \kappa_\alpha \cdot \omega_\alpha^m (1 - \omega_\alpha)^{n-m}} \quad (\alpha = 1, 2, 3, \dots).$$

Similarly that complex  $F_2$  was the origin:

$$Q_2 = \frac{\kappa_2 \cdot \omega_2^m (1 - \omega_2)^{n-m}}{\sum \kappa_\alpha \cdot \omega_\alpha^m (1 - \omega_\alpha)^{n-m}}$$

and so on for the other complexes.

*Proof.*—Let the number of equally possible cases in the general domain of action, which leads to one of the complexes  $F_\alpha$ , be  $t$ . Furthermore, of these  $t$  cases let  $f_1$  be favorable for the existence of complex  $F_1$ ,  $f_2$  for  $F_2$ ,  $f_3$  for  $F_3$ ,  $\dots$ , etc. Then the probabilities for the existence of the different complexes  $F_\alpha$  ( $\alpha = 1, 2, 3, \dots n$ ) are:

$$\kappa_1 = \frac{f_1}{t}, \quad \kappa_2 = \frac{f_2}{t}, \quad \kappa_3 = \frac{f_3}{t} \dots \text{respectively.}$$

Of the  $f_1$  favorable cases for complex  $F_1$ ,  $\lambda_1$  are also favorable for the occurrence of  $E$ .

Of the  $f_2$  favorable cases for complex  $F_2$ ,  $\lambda_2$  are also favorable for the occurrence of  $E$ .

Of the  $f_3$  favorable cases for complex  $F_3$ ,  $\lambda_3$  are also favorable for the occurrence of  $E$ .

The probability of the happening of  $E$  under the assumption that  $F_1$  exists, i. e., the relative probability:  $P_{F_1}(E)$ , is:

$$\omega_1 = \frac{\lambda_1}{f_1}$$

or in general:

$$\omega_\alpha = \frac{\lambda_\alpha}{f_\alpha} \quad (\alpha = 1, 2, 3, \dots).$$

The total number of equally likely cases for the simultaneous occurrence of the event  $E$  with either one of the favorable cases

for  $F_1, F_2, F_3, \dots$  is:

$$\lambda_1 + \lambda_2 + \lambda_3 + \dots = \Sigma \lambda_a.$$

The number of favorable cases for the simultaneous occurrence of  $F_1$  and  $E$  is  $\lambda_1$ , for the simultaneous occurrence of  $F_2$  and  $E$ ,  $\lambda_2, \dots$ , etc. Hence: we have as measures for their corresponding probabilities

$$Q_1 = \frac{\lambda_1}{\Sigma \lambda_a}, \quad Q_2 = \frac{\lambda_2}{\Sigma \lambda_a}, \quad \dots$$

But

$$\lambda_1 = \omega_1 \cdot f_1, \quad \lambda_2 = \omega_2 \cdot f_2, \quad \dots, \quad \text{etc.,}$$

and

$$f_1 = \kappa_1 \cdot t, \quad f_2 = \kappa_2 \cdot t, \quad \dots, \quad \text{etc.}$$

Hence

$$\lambda_1 = \omega_1 \cdot \kappa_1 \cdot t, \quad \lambda_2 = \omega_2 \cdot \kappa_2 \cdot t, \quad \dots, \quad \text{etc.}$$

Substituting these values in the above expression for  $Q_1, Q_2, \dots$  we get:

$$Q_1 = \frac{\kappa_1 \cdot \omega_1}{\Sigma \kappa_a \cdot \omega_a}, \quad Q_2 = \frac{\kappa_2 \cdot \omega_2}{\Sigma \kappa_a \cdot \omega_a}, \quad \dots$$

as the respective probabilities that the observed event originated from the complexes  $F_1, F_2, F_3, \dots$ . Such probabilities are called a posteriori probabilities.

Let us now for a moment investigate the above expression for  $Q_1, Q_2, \dots$ . The numerator in the expression for  $Q_1$  is  $\kappa_1 \cdot \omega_1$ . But  $\kappa_1$  is simply the a priori probability for the existence of  $F_1$  while  $\omega_1$  is the a priori productive probability of bringing forth the event observed from complex  $F_1$ . The product  $\kappa_1 \cdot \omega_1$  is simply the relative probability  $P_{F_1}(E)$ , or the probability that the event  $E$  originated from  $F_1$ . In the denominator we have the expression  $\Sigma \kappa_a \omega_a$  ( $\alpha = 1, 2, \dots n$ ) which is the total probability to get  $E$  from any of the complexes  $F_a$ . From example 17 (Chapter IV) we know that the probability to get  $E$  exactly  $m$  times from  $F_1$  in  $n$  total trials is:

$$p_1 = \binom{n}{m} \kappa_1 \cdot \omega_1^m (1 - \omega_1)^{n-m}$$

and the probability to get  $E$  from any one of the complexes,  $F$ ,

$m$  times out of  $n$  is:

$$\Sigma p_{\alpha} = \binom{n}{m} \Sigma \kappa_{\alpha} \cdot \omega_{\alpha}^m (1 - \omega_{\alpha})^{n-m} \quad (\alpha = 1, 2, 3, \dots).$$

If, by actual observation, we know the event  $E$  to have happened exactly  $m$  times out of  $n$ , then the a posteriori probability that  $F_1$  was the origin is:

$$Q_1 = \frac{\binom{n}{m} \kappa_1 \cdot \omega_1^m (1 - \omega_1)^{n-m}}{\Sigma \binom{n}{m} \kappa_{\alpha} \cdot \omega_{\alpha}^m (1 - \omega_{\alpha})^{n-m}} \quad (\alpha = 1, 2, 3, \dots). \quad (I)$$

The factorials  $\binom{m}{n}$  in numerator and denominator cancel each other of course. It will be noticed that, in the above proof, it is not assumed that the a posteriori probability is proportional to the a priori probability, an assumption usually made in the ordinary texts on algebra.

**42. Bayes's Rule (Case II).—***(Special Case. The a priori probabilities of existence of the different complexes are equal.)* Sometimes the different complexes  $F$  may be of such special characters that their a priori probabilities of existence are equal, i. e.,

$$\kappa_1 = \kappa_2 = \kappa_3 = \kappa_4 \cdots \kappa_n.$$

In this case the equation (I) simply reduces to:

$$Q_1 = \frac{\omega_1^m (1 - \omega_1)^{n-m}}{\Sigma \omega_{\alpha}^m (1 - \omega_{\alpha})^{n-m}}. \quad (II)$$

Equation (I) gives, however, the most general expression for Bayes's Rule which may be stated as follows:

*If a definite observed event,  $E$ , can originate from a certain series of mutually exclusive complexes,  $F$ , and if the actual occurrence of the event has been observed, then the probability that it originated from a specified complex or a specified group of complexes is also the "a posteriori" probability or probability of existence of the specified complex or group of complexes.*

**43. Determination of the Probabilities of Future Events Based Upon Actual Observations.**—It happens frequently that

our knowledge of the general domain of action is so incomplete, that we are not able to determine, a priori, the probability of the occurrence of a certain expected event. As we already have stated in the introduction to a posteriori probabilities, this is nearly always the case with problems wherein organic life enters as a determining factor or momentum. But the same state of affairs may also occur in the category of problems relating to games of chance, which we have hitherto considered. Suppose we had an urn which was known to contain white and black balls only, but the actual ratio in which the balls of the two different colors were mixed, was unknown. With this knowledge beforehand, we should not be able to determine the probability for the drawing of a white ball. If, on the other hand, we knew, from actual experience by repeated observations, the results of former drawings from the same urn when the conditions in the general domain of action remained unchanged during each separate drawing, then these results might be used in the determination of the probability of a specified event by future drawings.

Our problem may be stated in its most general form as follows: Let  $F_a$  denote a certain state or condition in the general domain of action, which state or condition can appear only in one or the other of the mutually exclusive forms:  $F_1, F_2, F_3, \dots$ , and not otherwise. Let the probability of existence of  $F_1, F_2, F_3, \dots$  be  $\kappa_1, \kappa_2, \kappa_3, \dots$  respectively, and when one of the complexes  $F_1, F_2, F_3, \dots$  exists (occurs) let  $\omega_1, \omega_2, \omega_3, \dots$  be the respective productive probabilities of bringing forth a specified event,  $E$ . If now, by actual observation, we know the event,  $E$ , to have happened exactly  $m$  times out of  $n$  total trials (the conditions in the general domain of action being the same at each individual trial), what is then the probability that the event,  $E$ , will happen in the  $(n+1)$ th trial also?

By Bayes's Rule we determined the "a posteriori" probabilities or the probabilities of existence of the complexes  $F_1, F_2, \dots$  as:

$$Q_1 = \frac{\kappa_1 \cdot \omega_1^m (1 - \omega_1)^{n-m}}{\sum \kappa_a \cdot \omega_a^m (1 - \omega_a)^{n-m}}, \quad Q_2 = \frac{\kappa_2 \cdot \omega_2^m (1 - \omega_2)^{n-m}}{\sum \kappa_a \cdot \omega_a^m (1 - \omega_a)^{n-m}}, \quad \dots$$

( $\alpha = 1, 2, 3, \dots$ ).

In the  $(n+1)$ th trial  $E$  may happen from any one of the mutually

exclusive complexes:  $F_1, F_2, F_3, \dots$  whose respective probabilities in producing the event,  $E$ , are  $\omega_1, \omega_2, \omega_3, \dots$ . The addition theorem then gives us as the total probability of the occurrence of  $E$  in the  $(n+1)$ th trial:

$$R_n = \Sigma P_{F_n}(E) = Q_1 \cdot \omega_1 + Q_2 \cdot \omega_2 + Q_3 \cdot \omega_3 \\ + \dots = \frac{\Sigma \kappa_n \cdot \omega_n^m (1 - \omega_n)^{n-m} \cdot \omega_n}{\Sigma \kappa_n \cdot \omega_n^m (1 - \omega_n)^{n-m}} \quad (\alpha = 1, 2, 3, \dots). \quad (\text{III})$$

If the a priori probabilities of existence are of equal magnitude (Case II) the factors  $\kappa$  in the above expression cancel each other in numerator and denominator and we have

$$R = \frac{\Sigma \omega_n^m (1 - \omega_n)^{n-m} \omega_n}{\Sigma \omega_n^m (1 - \omega_n)^{n-m}}. \quad (\text{IV})$$

**44. Examples on the Application of Bayes's Rule.**—*Example 21.*—An urn contains two balls, white or black or both kinds. What is the probability of getting a white ball in the first drawing, and if this event has happened and the ball replaced, what is then the probability to get white in the following drawing?

Three conditions are here possible in the urn. There may be 0, 1, or 2 white balls. Each hypothetical condition has a probability of existence equal to  $\frac{1}{3}$ , and the productive probabilities for white are 0,  $\frac{1}{2}$  and 1 respectively. The total probability to get white is therefore:

$$p_1 = \frac{1}{3} \cdot 0 + \frac{1}{3} \cdot \frac{1}{2} + \frac{1}{3} \cdot 1 = \frac{1}{2}.$$

If we now draw a white ball then the probabilities that it came from the complexes:  $F_1, F_2, F_3$ , respectively, are:

$$0 \div \frac{1}{2}, \quad \frac{1}{2} \div \frac{1}{2}, \quad \frac{1}{2} \div \frac{1}{2}.$$

These are also new existence probabilities of the three probabilities. The probability for white in second drawing is therefore.

$$(0 \div \frac{1}{2})0 + (\frac{1}{2} \div \frac{1}{2})\frac{1}{2} + (\frac{1}{2} \div \frac{1}{2})1 = \frac{3}{4}.$$

This solution of the problem is, however, not a unique solution, because it is an arbitrary solution. It is arbitrary in this respect, that we have without further consideration given all three complexes the same probability of existence,  $\frac{1}{3}$ . We shall discuss

this part of the question under the chapter on the criticism of Bayes's Rule.

*Example 22.*—An urn contains five balls of which a part is known to be white and the rest black. A ball is drawn four times in succession and replaced after each drawing. By three of such drawings a white ball was obtained and by one drawing a black ball. What is the probability that we will get a white ball in the fifth drawing?

In regard to the contents of the urn the following four hypotheses are possible:

|         |   |        |   |       |        |
|---------|---|--------|---|-------|--------|
| $F_1$ : | 4 | white, | 1 | black | balls, |
| $F_2$ : | 3 | "      | 2 | "     | "      |
| $F_3$ : | 2 | "      | 3 | "     | "      |
| $F_4$ : | 1 | "      | 4 | "     | "      |

Since we do not know anything about the ratio of distribution of the different colored balls, we may by a direct application of the principle of insufficient reason regard the four complexes as equally probable, or:

$$\kappa_1 = \kappa_2 = \kappa_3 = \kappa_4 = \frac{1}{4}.$$

If either  $F_1$ ,  $F_2$ ,  $F_3$  or  $F_4$  exists, the respective productive probabilities are:

$$\omega_1 = \frac{4}{5}, \quad \omega_2 = \frac{3}{5}, \quad \omega_3 = \frac{2}{5}, \quad \omega_4 = \frac{1}{5}.$$

By a direct substitution in the formula:

$$R = \frac{\sum \omega_a^m (1 - \omega_a)^{n-m} \cdot \omega_a}{\sum \omega_a^m (1 - \omega_a)^{n-m}}$$

( $\alpha = 1, 2, 3, 4$ ) for  $n = 4$  and  $m = 3$  we get:

$$R = \frac{\left(\frac{4}{5}\right)^3 \left(\frac{1}{5}\right) \left(\frac{4}{5}\right) + \left(\frac{3}{5}\right)^3 \left(\frac{2}{5}\right) \left(\frac{3}{5}\right) + \left(\frac{2}{5}\right)^3 \left(\frac{3}{5}\right) \left(\frac{2}{5}\right) + \left(\frac{1}{5}\right)^3 \left(\frac{4}{5}\right) \left(\frac{1}{5}\right)}{\left(\frac{4}{5}\right)^3 \left(\frac{1}{5}\right) + \left(\frac{3}{5}\right)^3 \left(\frac{2}{5}\right) + \left(\frac{2}{5}\right)^3 \left(\frac{3}{5}\right) + \left(\frac{1}{5}\right)^3 \left(\frac{4}{5}\right)} = \frac{47}{8}.$$

**45. Criticism of Bayes's Rule.**—In most English treatises on the theory of chance the "a posteriori" determination of a mathematical probability is discussed under the so-called "inverse probabilities." This somewhat misleading name was probably first introduced by the eminent English mathematician and actuary, Augustus de Morgan. In the opening of the discussion

of a posteriori probabilities in the third chapter of his treatise, "An Essay on Probabilities," de Morgan says: "In the preceding chapter, we have calculated the chances of an event, knowing the circumstances under which it is to happen or fail. We are now to place ourselves in an inverted position, we know the event, and ask what is the probability which results from the event in favor of any set of circumstances under which the same might have happened." Is this now an inverse process? By the a priori or—as de Morgan prefers to call them,—the direct probabilities, we started from a definitely known condition and determined the probability for a future event, *E*, or what is the same, the probability of a specified future state of affairs. Here we start knowing the present condition and try to determine a past condition. The process apparently appears to be the inverse of the former, although they both are the same. We possess a definite knowledge of a certain condition and try to determine the probability of the existence of a specified state of affairs, in general different from the first condition, but whether this state of affairs occurred in the past or is to occur in the future has no bearing on our problem. In other words, time does not enter as a determining factor. And even if we were willing to admit the two processes of the determination of the different probabilities to be inverse, the probabilities themselves can not be said to be inverse. Nevertheless, this misleading name appears over and over again in examination papers in England and in America as a thoroughly embalmed corpse which ought to have been buried long ago. What is really needed, is a change of customary nomenclature in the whole theory of probability. Instead of direct and inverse, a priori and a posteriori probabilities, it would be more proper to speak about "prospective" and "retrospective" probabilities in the application of Bayes's Rule. All probabilities are in reality determined by an empirical process. That there is a certain probability to throw a six with a die we only know after we have formed a definite conception of a die. The only probabilities which we perhaps rightly may name a priori are the arbitrary probabilities in purely mathematical problems where we assume an ideal state of affairs. "There is," to quote the Danish writer on logic, Dr. Kroman, "really

more reason to doubt the *a priori* than the *a posteriori* probabilities, and it would be more natural and also more exact in the application of Bayes's Rule to speak about the actual or original and the new or gained probability."

The discussion above has really no direct bearing on Bayes's Rule but was introduced in order to give the student a clearer understanding of the main principles underlying the whole determination of *a posteriori* probabilities by means of actual experimental observations, and also to remove some obscure points. From his ordinary mathematical training every student of mathematics has an almost intuitive understanding of an inverse process. Naturally when he encounters again and again the customary heading: "inverse probabilities" in text-books he obtains from the very start—almost before he starts to read this particular chapter—an inverse idea of the subject instead of the idea he really ought to have. Nowhere in continental texts on the theory of probabilities, will the reader be able to find the words direct and inverse applied in the same sense as in English texts since the introduction of these terms by de Morgan. We shall advise readers who have become accustomed to the old terms to pay no serious attention to them.

**46. Theory Versus Practice.**—In § 41 we reduced Bayes's Rule to its most general form:

$$Q = \frac{\kappa_a \cdot \omega_a^m (1 - \omega_a)^{n-m}}{\sum \kappa_a \cdot \omega_a^m (1 - \omega_a)^{n-m}} \quad (\alpha = 1, 2, 3, \dots).$$

This is an exact expression for the rule, but it is at the same time almost impossible to employ it in practice. Only in a few exceptional cases do we know, *a priori*, the different values of the often numerous probabilities of existence  $\kappa_a$ , of the complexes  $F_a$ , and in order to apply the rule with exact results we require here sufficient facts and information about the different complexes of causes from which the observed event,  $E$ , originated. Bayes deduced the rule from special examples resulting from drawings of balls of different colors from an urn where the different complexes of causes were materially existent. The probability of a cause or a certain complex of causes did not here mean the probability of existence of such a complex but the probability

that the observed event originated from this particular complex. In order to elucidate this statement we give following simple example:

*Example 23.*—A bag contains 4 coins, of which one is coined with two heads, the other three having both head and tail. A coin is drawn at random and tossed four times in succession and each time head turns up. What is the probability that it was the coin with two heads?

The two complexes  $F_1$  and  $F_2$ , which may produce the event,  $E$ , are:  $F_1$ , the coin with two heads, and  $F_2$ , an ordinary coin. The probability of existence of  $F_1$  is the probability of drawing the single coin with two heads which is equal to  $\frac{1}{4}$ , the probability of existence for the other complex,  $F_2$ , is equal to  $\frac{3}{4}$ . The respective productive probabilities are 1 and  $\frac{1}{2}$ . Thus  $\kappa_1 = \frac{1}{4}$ ,  $\kappa_2 = \frac{3}{4}$ ,  $\omega_1 = 1$  and  $\omega_2 = \frac{1}{2}$ . Substituting these values in formula (I) ( $n = 4$ ,  $m = 4$ ), we get:

$$Q = (\frac{1}{4} \times 1^4) \div (\frac{1}{4} \times 1^4 + \frac{3}{4} \times (\frac{1}{2})^4) = \frac{1}{4} \div \frac{19}{64} = \frac{16}{19}.$$

But in most cases we do not know anything about the material existence of the complexes of causes from which the event,  $E$ , originated. On the contrary, we are forced to form a hypothesis about their actual existence. To start with a simple case we take example 21 of § 44.

We assumed here three equally possible conditions in the urn before the drawings, namely the presence of 0, 1, or 2 white balls. From this assumption we found the probability to get a white ball in the second drawing, after we had previously drawn a white ball and then put it back in the urn before the second drawing, to be equal to  $\frac{5}{8}$ . As we already remarked, this solution is not unique because it is an arbitrary solution. It is arbitrary to assign, without any consideration whatsoever,  $\frac{1}{3}$  as the probability of existence to each of the three conditions. Let us suppose that each of the two balls bore the numbers 1 and 2 respectively. We may then form the following equally likely conditions:

$$b_1b_2, b_1w_2, b_2w_1, w_1w_2,$$

each condition having an a priori probability of existence equal to  $\frac{1}{4}$  and a productive probability for the drawing of a white

ball equal to: 0,  $\frac{1}{2}$ ,  $\frac{1}{2}$  and 1 respectively. Thus:

$$\kappa_1 = \kappa_2 = \kappa_3 = \kappa_4 = \frac{1}{4}$$

and

$$\omega_1 = 0, \quad \omega_2 = \frac{1}{2}, \quad \omega_3 = \frac{1}{2}, \quad \omega_4 = 1.$$

The respective a posteriori probabilities, that is the new or gained probabilities of the four hypothetical conditions, become now by the application of Bayes's Rule (Formula II):

$$Q_1 = \frac{0}{2}, \quad Q_2 = \frac{1}{2} \div 2, \quad Q_3 = \frac{1}{2} \div 2, \quad Q_4 = \frac{1}{2}.$$

Hence the probability for white in the second drawing is:

$$\left( \text{Formula IV: } R = \frac{\sum \omega_a^m (1 - \omega_a)^{n-m} \omega_a}{\sum \omega_a^m (1 - \omega_a)^{n-m}} \right)$$

$$R = 0 \div 2 + (\frac{1}{4} \div 2) + (\frac{1}{4} \div 2) + (1 \div 2) = \frac{3}{4}.$$

In the first solution we got  $\frac{5}{8}$  for the same probability. Which answer is now the true one? Neither one! The true answer to the problem is that it is not given in such a form that the last question—the probability of getting a white ball in the second drawing—may be settled without any doubt. The answer must be conditional. Following the first hypothesis we got  $\frac{5}{8}$ , while the second hypothesis gives  $\frac{3}{4}$  as the answer.

We next proceed to example 22 which is almost identical in form to the first one, the only difference being a greater variety of hypothetical conditions. We started here with the following four hypotheses:

$F_1$ : 4 white, 1 black ball,  $F_2$ : 3 white, 2 black,  $F_3$ : 2 white, 3 black and  $F_4$ : 1 white and 4 black balls, assigning  $\frac{1}{4}$  as the hypothetical existence probability.

By marking the 5 balls similarly as in the last example, with the numbers from 1 to 5 we may form the complexes:

$$\begin{array}{llllll} F_1: & 4 & \text{white and 1 black ball in } (\frac{5}{1}) & \text{ways,} \\ F_2: & 3 & \text{" " 2 " balls " } (\frac{5}{2}) & \text{"} \\ F_3: & 2 & \text{" " 3 " " " } (\frac{5}{3}) & \text{"} \\ F_4: & 1 & \text{" " 4 " " " } (\frac{5}{4}) & \text{"} \end{array}$$

This gives us a total of  $5 + 10 + 10 + 5 = 30$  different complexes. Assuming all of these complexes equally likely

to occur, we get following probabilities of existence and productive probabilities:

$$\kappa_1 = \kappa_2 = \kappa_3 = \kappa_4 = \dots = \kappa_{30} = \frac{1}{30}$$

$$\omega_1 = \omega_2 = \omega_3 = \omega_4 = \omega_5 = \frac{4}{5} \text{ (Productive prob. for } F_1)$$

$$\omega_6 = \omega_7 = \omega_8 = \dots = \omega_{15} = \frac{3}{5} \text{ (Productive prob. for } F_2)$$

$$\omega_{16} = \omega_{17} = \dots = \omega_{25} = \frac{2}{5} \text{ (Productive prob. for } F_3)$$

$$\omega_{26} = \omega_{27} = \omega_{28} = \omega_{29} = \omega_{30} = \frac{1}{5} \text{ (Productive prob. for } F_4).$$

The total probability of getting a white ball in the second drawing is now  $\frac{\sum \omega_\alpha^2 (1 - \omega_\alpha) \omega_\alpha}{\sum \omega_\alpha^3 (1 - \omega_\alpha)}$  ( $\alpha = 1, 2, 3, \dots, 30$ ).

Actual substitution of the above values of  $\omega$  in this formula gives us the final result as:  $R = \frac{1}{2} \frac{7}{8}$ .

**47. Probabilities Expressed by Integrals.**—By making an extended use of the infinitesimal calculus Mr. Bing and Dr. Kroman in their memoirs arrived at much more ambiguous results through an application of the rule of Bayes. Starting with the fundamental rule as given in equation (I) in § 41, we may at times encounter somewhat simpler conditions inside the domain of causes. The total complex of actions may embrace a large number of smaller sub-complexes construed in such a way that the change from one complex to another may be regarded as a continuous process, so that the productive probabilities are increased by an infinitely small quantity from a certain lower limit,  $a$ , to an upper limit,  $b$ . Denoting such continuously increasing probabilities by  $v$  and the corresponding small probabilities of existence by  $u dv$ , we have as the total probability of obtaining  $E$  from any one of the minor complexes with a productive probability between  $\alpha$  and  $\beta$  ( $\alpha \geq a, \beta \leq b$ )

$$p = \int_a^\beta u dv.$$

The probability that when  $E$  has happened it originated from one of those minor complexes, or the probability of existence of some one of those complexes is:

$$P = \frac{\int_a^\beta u dv}{\int_a^b u dv}.$$

The situation may be still more simplified by the following considerations. In the continuous total complex between the limits  $a$  and  $b$  we have altogether situated  $(b - a)/dv$  individual minor complexes. If we assume all of these complexes to possess the same probability of existence, we must have:

$$udv = \frac{dv}{b - a}.$$

The two formulas then take on the form:

$$p = \frac{1}{b - a} \int_a^b v dv$$

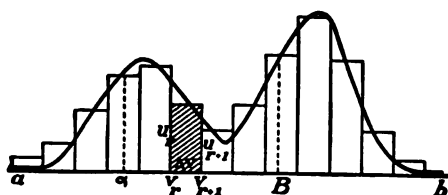
and

$$P = \frac{\int_a^b v dv}{\int_a^b v dv}.$$

A still more specialized form is obtained by letting  $a = 0$  and  $b = 1$  which gives:

$$p = \int_a^b v dv \quad \text{and} \quad P = \frac{\int_a^b v dv}{\int_0^1 v dv}.$$

The above formulas may perhaps be made more intelligible to the reader by a geometrical illustration.



Let the various productive probabilities,  $v$ , be plotted along the  $X$  axis in a Cartesian coördinate system in the interval from  $a$  to  $b$  ( $a < b$ ). To any one of these probabilities say  $v_r$  there corresponds a certain probability of existence,  $u_r$ , represented by a  $Y$  ordinate. In the same manner the next following productive probability,  $v_{r+1}$ , will have a probability of existence

represented by an ordinate  $u_{r+1}$ . It is now possible to represent the various  $u$ 's by means of areas instead of line ordinates. Thus the probability of existence,  $u_r$ , is in the figure represented by the small shaded rectangle, with a base equal to

$$v_{r+1} - v_r = \Delta v_r,$$

and an altitude of  $u_r$ , the total area being equal to  $\Delta v_r u_r$ . That this is so, follows from the well-known elementary theorem from geometry that areas of rectangles with equal bases are directly proportional to their altitudes. The sum of the different  $u$ 's is thus in the figure represented as the sum areas of the various small rectangles in the staircase shaped histogram. Now according to our assumption  $v$  is a continuous function in the interval from  $a$  to  $b$ . We may, therefore, divide this interval,  $b - a$ , into  $n$  smaller equal intervals. Let

$$v_{r+1} - v_r = \Delta v_r = \frac{b - a}{n}$$

be one of these smaller divisions. By choosing  $n$  sufficiently large,  $(b - a)/n$  or  $\Delta v$  becomes a very small quantity and by letting  $n$  approach infinity as a limiting value we have

$$\lim_{n \rightarrow \infty} u \frac{b - a}{n} = \lim_{\Delta v \rightarrow 0} u \Delta v = u dv.$$

In this case the histogram is replaced by a continuous curve and  $u dv$  is the probability of existence that the productive probability is enclosed between  $v$  and  $v + dv$ .<sup>1</sup>

The probability to get  $E$  from any one of the complexes is evidently given by the total area of the small rectangles, or in the continuous case by means of the integral:

$$\int_a^b u dv.$$

<sup>1</sup> A more rigorous analysis would be as follows: We plot along the abscissa axis intervals of the length  $\epsilon$  so that the middle of the interval has a distance from the origin equal to an integral multiple of  $\epsilon$ . If now  $\epsilon$  is chosen sufficiently small, we may regard the probability of existence of  $u$ , for values of the variable  $v$  between  $v_\epsilon - \frac{1}{2}\epsilon$  and  $v_\epsilon + \frac{1}{2}\epsilon$  as a constant and the probability that  $v$  falls between the limits  $v_\epsilon - \frac{1}{2}\epsilon$  and  $v_\epsilon + \frac{1}{2}\epsilon$  may hence be expressed as  $\epsilon u_\epsilon$ . When  $\epsilon$  approaches 0 as a limiting value this expression becomes  $u dv$ . See the similar discussion under frequency curves.

In the same way the probability that  $E$  originated from any of the complexes between  $\alpha$  and  $\beta$  is:

$$\frac{\int_a^b u v d\alpha}{\int_a^b u v d\beta}.$$

The special case  $a = 0$  and  $b = 1$  needs no further commentary.

We are now in a position to consider the examples of Bing and Kroman. Any student familiar with multiple integration will find no difficulty in the following analysis. For the benefit of readers to whom the evaluation of the various integrals may seem somewhat difficult, we may refer to the addenda at the close of this treatise or to any standard treatise on the calculus as, for instance, Williamson's "Integral Calculus."

**48. Example 24.**—An urn contains a very large number of similarly shaped balls. In 10 successive drawings (with replacements) we have obtained 7 with the number 1, 2 with the number 2, and one having the number 3. What is the probability to obtain a ball with another number in the following drawing?

We must here distinguish between 4 kinds of balls, namely balls marked 1, 2, 3, or "other balls." A general scheme of distribution of the balls in the urn may be given through the following scheme:

$$\begin{array}{llllll} nx & \text{balls marked with the number 1,} \\ ny & \text{" " " " " 2,} \\ nz & \text{" " " " " 3 and} \\ nt & = n(1 - x - y - z) \text{ other balls.} \end{array}$$

Here  $x$ ,  $y$ ,  $z$  and  $t$  represent the respective productive probabilities. If we now let all such probabilities assume all possible values between 0 and 1 with intervals of  $1/n$ , we obtain the possible conditions in the total complex of actions. Each of these conditions has a probability of existence,  $s$ , and the productive probabilities  $x$ ,  $y$ ,  $z$ , and  $1 - x - y - z$ . The original probability for 7 ones, 2 twos and 1 three in 10 drawings is:

$$P = \frac{10!}{7!2!1!} \Sigma s \cdot x^7 \cdot y^2 \cdot z.$$

Now when  $n$  is a very large number the interval  $1/n$  becomes a very small quantity, and we may approximately write:

$$s = u dx dy dz,$$

and also write the above sum as a triple integral:

$$P = \frac{10!}{7!2!1!} \int_0^1 \int_0^x \int_0^y u \cdot x^7 \cdot y^2 \cdot z \cdot dx \cdot dy \cdot dz,$$

where

$$p = 1 - x \quad \text{and} \quad q = 1 - x - y.$$

If now the above event has happened, then the probability to get a different marked ball in the 11th drawing is:

$$Q = \frac{\int_0^1 \int_0^x \int_0^y u \cdot x^7 \cdot y^2 \cdot z(1 - x - y - z) \cdot dx \cdot dy \cdot dz}{\int_0^1 \int_0^x \int_0^y u \cdot x^7 \cdot y^2 \cdot z \cdot dx \cdot dy \cdot dz}.$$

It is, however, quite impossible to evaluate the above integral without knowing the form of the function  $u$ ; but unfortunately our information at hand tells us absolutely nothing in regard to this. Perhaps the balls bear the numbers 1, 2 and 3 only, or perhaps there is an equal distribution up to 10,000 or any other number. Our information is really so insufficient that it is quite hopeless to attempt a calculation of the a posteriori probability.

Many adherents of the inverse probability method venture, however, boldly forth with the following solution based upon the perfectly arbitrary hypothesis that all the  $u$ 's are of equal magnitude. This gives the special integral:

$$Q = \frac{\int_0^1 \int_0^x \int_0^y x^7 \cdot y^2 \cdot z(1 - x - y - z), dx \cdot dy \cdot dz}{\int_0^1 \int_0^x \int_0^y x^7 \cdot y^2 \cdot z \cdot dx \cdot dy \cdot dz}$$

where once more it must be remembered that

$$x + y + z \leq 1.$$

In this case the limits of  $x$  are 0 and 1, those of  $y$  are 0 and  $1 - x$  and those of  $z$  are 0 and  $1 - x - y$ .

This is a well-known form of the triple integral which may be evaluated by means of Dirichlet's Theorem:

$$U = \int_0^1 \int_0^{1-x} \int_0^{1-x-y} x^{b-1} y^{m-1} z^{n-1} dx \cdot dy \cdot dz = \frac{\Gamma(b)\Gamma(m)\Gamma(n)}{\Gamma(1+b+m+n)}.$$

(See Williamson's Calculus.)

Remembering the well-known relation between gamma functions and factorials, viz.  $\Gamma(n+1) = n!$ , we find by a mere substitution in the integral, the value of the probability in question to be 1:14. Another and equally plausible result is obtained by a slightly different wording of the problem.

Ten successive drawings have resulted in balls marked 1, 2, or 3. What is the probability to obtain a ball not bearing such a number in the 11th drawing? This probability is given by the formula.

$$\frac{\int_0^1 v^{10}(1-v)dv}{\int_0^1 v^{10}dv} = 1:12.$$

Quite a different result from the one given above.

**49. Example 25—Bing's Paradox.**—A still more astonishing paradox is produced by Bing when he gives an example of Bayes's Rule to a problem from mortality statistics. A mortality table gives the ratio of the number of persons living during a certain period, to the number living at the beginning of this period, all persons being of the same age. By recording the deaths during the specified period (say one year) it has been ascertained that of  $s$  persons, say forty years of age at the beginning of the period,  $m$  have died during the period. The observed ratio is then  $(s-m)/s$ . If  $s$  is a very large number this ratio may (as we shall have occasion to prove at a later stage) be taken as an approximation of the true ratio of probability of survival during the period. If  $s$  is not sufficiently large the believers in the inverse theory ought to be able to evaluate this ratio by an application of Bayes's Rule, by means of an analysis similar to the one as follows:

Let  $y$  be the general symbol for the probability of a forty-year-old person being alive one year from hence. Each of such persons will in general be subject to different conditions, and the general symbol,  $y$ , will therefore have to be understood as the

symbol for all the possible productive probability values changing from 0 to 1 by a continuous process.

Assuming  $s$  a very large number each condition will have a probability of existence equal to  $udy$ . We may now ask: What is the probability that the rate of survival of a group of  $s$  persons aged 40 is situated between the limits  $\alpha$  and  $\beta$ ?

The answer according to Bayes's Rule is:

$$\frac{\int_{\alpha}^{\beta} y^{s-m}(1-y)^m u dy}{\int_0^1 y^{s-m}(1-y)^m u dy}. \quad (\text{I})$$

Let us furthermore divide the whole year into two equal parts and let  $y_1$  be the probability of surviving the first half year,  $y_2$  the probability of surviving the second half, and  $u_1 \cdot dy_1$ ,  $u_2 \cdot dy_2$  the corresponding probabilities of existence. Then the respective a posteriori probabilities for  $y_1$  and  $y_2$  are:

$$\frac{y_1^{s-m_1}(1-y_1)^{m_1} u_1 dy_1}{\int_0^1 y_1^{s-m_1}(1-y_1)^{m_1} u_1 dy_1}$$

and

$$\frac{y_2^{s-m_2}(1-y_2)^{m_2} u_2 dy_2}{\int_0^1 y_2^{s-m_2}(1-y_2)^{m_2} u_2 dy_2} \quad (m_1 + m_2 = m)$$

( $m_1$  and  $m_2$  represent the number of deaths in the respective half years.) The probability that both  $y_1$  and  $y_2$  are true is then according to the multiplication theorem:

$$\frac{y_1^{s-m_1}(1-y_1)^{m_1} u_1 dy_1 y_2^{s-m_2}(1-y_2)^{m_2} u_2 dy_2}{\int_0^1 y_1^{s-m_1}(1-y_1)^{m_1} u_1 dy_1 \int_0^1 y_2^{s-m_2}(1-y_2)^{m_2} u_2 dy_2}$$

where  $y = y_1 \cdot y_2$ .

The probability that the probability of survival for a full year,  $y$ , is situated between the limits  $\alpha$  and  $\beta$  is therefore:

$$\frac{\int \int y_1^{s-m_1}(1-y_1)^{m_1} y_2^{s-m_2}(1-y_2)^{m_2} u_1 \cdot u_2 \cdot dy_1 \cdot dy_2}{\int_0^1 y_1^{s-m_1}(1-y_1)^{m_1} u_1 dy_1 \int_0^1 y_2^{s-m_2}(1-y_2)^{m_2} u_2 dy_2} \quad (\text{II})$$

where the limits in the double integral in the numerator are determined by the relation:

$$\alpha \leq y_1 y_2 \leq \beta.$$

Choosing the principle of insufficient reason as the basis of our calculations, merely assuming that all possible events are, in the absence of any grounds for inference, equally likely, the various quantities expressed by the general symbol,  $u$ , become equal and constant and cancel each other in numerator and denominator, which brings the a posteriori probabilities expressed by (I) and (II) to the forms:

$$\frac{\int_{\alpha}^{\beta} y^{s-m}(1-y)^m dy}{\int_0^1 y^{s-m}(1-y)^m dy} \quad (\text{III})$$

and

$$\frac{\int \int y_1^{s-m_1}(1-y_1)^{m_1} y_2^{s-m_1-m_2}(1-y_2)^{m_2} dy_1 \cdot dy_2}{\int_0^1 y_1^{s-m_1}(1-y_1)^{m_1} \int_0^1 y_2^{s-m}(1-y_2)^{m_2} dy_1 \cdot dy_2} \quad (\text{IV})$$

where the limits in the numerator in the latter expression are determined by the relation :  $\alpha < y_1 y_2 < \beta$ .

Letting

$$y_2 = \frac{y}{y_1}$$

and then

$$1 - y_1 = z(1 - y)$$

this latter expression may after a simple substitution be brought to the form:

$$\frac{\int_{\alpha}^{\beta} y^{s-m}(1-y)^{m+1} dy \int_0^1 \frac{z^{m_1}(1-z)^{m_2} dz}{1-z(1-y)}}{\int y_1^{s-m_1}(1-y_1)^{m_1} dy_1 \int_0^1 y_2^{s-m}(1-y_2)^{m_2} dy_2}. \quad (\text{V})$$

(See appendix.)

Mr. Bing now puts the further question: What is the probability that a new person forty years of age, entering the original large

group of  $s$  persons, will survive one year, when we assume  $m_1 = m_2 = 0$ ? (III) gives the answer:

$$\frac{\int_0^1 y^{s+1} dy}{\int_0^1 y^s dy} = \frac{s+1}{s+2}.$$

Formula (V), on the other hand, gives us:

$$\frac{\int_0^1 y^{s+1}(1-y) dy \int_0^1 \frac{dz}{1-z(1-y)}}{\int_0^1 y_1^s dy_1 \int_0^1 y_2^s dy_2} = \left(\frac{s+1}{s+2}\right)^2.$$

As the above analysis is perfectly general, we might equally well have applied it to each of the semi-annual periods, which would give us an a posteriori probability of survival equal to  $\left(\frac{s+1}{s+2}\right)^2$  for each half year, or a compound probability of  $\left(\frac{s+1}{s+2}\right)^4$  for the whole year. Extending this process it is easily seen that by dividing the year into parts, we shall have  $\left(\frac{s+1}{s+2}\right)^n$  as the final probability a posteriori that a forty-year-old person will reach the age of forty-one. By letting  $n$  increase indefinitely the above quantity approaches 0 as its limiting value and we obtain thus the paradox of Bing:

*If, among a large group of  $s$  equally old persons, we have observed no deaths during a full calendar year then another person of the same age outside the group is sure to die inside the calendar year.*

This is evidently a very strange result, and yet, working on the basis of the principle of insufficient reason, the mathematical deductions and formula exhibit no errors.

Mr. Bing disposes of the whole matter by simply denying the validity and existence of a posteriori probabilities. Dr. Kroman on the other hand defends Bayes's Rule. "Mathematics," Kroman says, "is—as Huxley has justly remarked—an exceedingly fine mill stone, but one must not expect to get wheat flour after having put oats in the quern." According to the

Danish scholar the paradox is due to the use of a wrong formula. We ought to have used the general formula (II) instead of formula (V) which is a special case. In the general formula we encounter the functions  $u$ , denoting the probability existence of the various productive probabilities  $y$ . As we do not know anything about this function  $u$  it is hopeless to attempt a calculation. This brings the criticism down to the fundamental question whether we shall build the theory of probabilities on the principle of "cogent reason" or the principle of "insufficient reason."

**50. Conclusion.**—Contradictory results of a similar kind to the ones given above have led several eminent mathematicians to a complete denunciation of the laws underlying a posteriori probabilities. Professor Chrystal, especially, becomes extremely severe in his criticism in the previously mentioned address before the Actuarial Society of Edinburgh. He advises "practical people like the actuaries, much though they may justly respect Laplace, not to air his weaknesses in their annual examinations. The indiscretions of a great man should be quietly allowed to be forgotten." Although one may heartily agree with Professor Chrystal's candid attack on the belief in authority, too often prevailing among mathematical students, I think—aside from the fact that the rule was originally given by Bayes—that the great French savant has been accused unjustly as the following remarks perhaps may tend to show.

In our statement of Bayes's Rule, we followed an exact mathematical method, and the final formula (I) is theoretically as correct as any previously demonstrated in this work. The customary definition of a mathematical probability as the ratio of equally favorable to coördinated possible cases, is not done away with in this new kind of probabilities; the former are found in the numerator and the latter in the denominator; and if we take care that each of the particular formulas, with its definite requirements, is applied to its particular case, we do not go beyond pure mathematics or logic. But are we able to get complete and exact information about these requirements? In the example of the tossing of a coin with two heads, this information was at hand. Here we were able to enumerate exactly the different mutually exclusive causes from which the observed

event originated. We were also able to determine the exact quantitative measures for the probabilities,  $\kappa$ , that these complexes existed as well as the different productive probabilities,  $\omega$ . Here the most rigid requirements could be satisfied, and the rule gave therefore a true answer.

In the other examples we encountered a different state of affairs. Here we were not able to enumerate directly the different complexes of causes from which the event originated, but were forced to form different and arbitrary hypotheses about the complexes of origin,  $F$ , and each hypothesis gave, in general, a different result. Furthermore, we assumed a priori that the different probabilities of the actual existence of the complexes were all equal in magnitude, and it was, therefore, the special formula (II) we employed in the determination of the a posteriori probabilities. In this formula, the different  $\kappa$ 's do not enter at all as a determining factor; only the productive probabilities,  $\omega$ , are considered. The assumption that all the  $\kappa$ 's are equal in magnitude is based upon the principle of insufficient reason, or as Boole calls it, "the equal distribution of ignorance."

The principle of equal distribution of ignorance makes in the case of continuously varying productive probabilities,  $v$ , the function,  $u$ , of the probabilities of existence of the various complexes equal to a constant quantity. In other words, the curve in Fig. 1, is replaced by a straight line of the form,  $u = k$ . Now, as a matter of fact, we possess in most cases, some partial knowledge of the complexes of action producing the event in question. This partial knowledge—although far from complete enough to make a rigorous use of formula (I)—is nevertheless sufficient to justify us in discarding completely any general hypothesis assuming such simple conditions as above. Such partial knowledge is, for instance, found in the Paradox of Bing. Here the rather absurd hypothesis was made that the possible values of the probability of surviving a certain period were equally probable. In other words, it is equally probable that there will die 0, 1, 2,  $\dots$ , or  $s$  persons in the particular period. "Common sense, however, tells us that it is far more probable that, for instance, 90 per cent. of a large number of forty-year-old persons will survive the period than no one or every one will die

in the same period " (Kroman). The indiscreet use of formula (II) therefore naturally leads to paradoxical results. On the other hand, the fallacy of the happy-go-lucky computers, employing the special case (II) of Bayes's Rule, as well as the critics of Laplace, lies in their failure to make a proper distinction between "equal distribution of ignorance" and "partial cogent reason," which latter expression properly may be termed "an unequal distribution of ignorance." If, despite the actual presence of such unequal distribution of ignorance, we still insist in using the special formula (II), which is only to be used in the case of an equal distribution of ignorance, it is no wonder we encounter ambiguous answers. Not the rule itself, its discoverer, or Laplace, but the indiscreet computer is the one to blame. Messrs. Bing, Venn and Chrystal, in their various criticisms, have filled the quern with some rather "wild oats" and expected to get wheat flour; and that one of those critics in his disappointment in not getting the expected flour should blame Laplace, is hardly just.

So much for the principle of "equal distribution of ignorance." It may be of interest to see how matters turn out when we like von Kries insist upon the principle of "cogent reason" as the true basis of our computations. The reader will quite readily see that a rigorous application of the Rule of Bayes in its most general form as given by formula (I) really tacitly assumes this very principle. In formula (I), we require not alone an exact enumeration of the various complexes from which the observed event may originate, but also an exact and complete information about the structure of such complexes in order to evaluate their various probabilities of existence. If such information is present, we can meet even the most stringent requirements of the general formula, and we will get a correct answer. But in the vast majority of cases, not to say all cases, such information is not at hand, and any attempt to make a computation by means of Bayes's Rule must be regarded as hopeless. We may, however, again remark that very seldom we are in complete ignorance of the conditions of the complexes, which is the same thing as saying that we are not in a position to employ the principle of equal distribution of ignorance in a rigorous manner. From

other experiments on the same kind of event, or from other sources, we may have attained some partial information, even if insufficient to employ the principle of cogent reason. Is such information now to be completely ignored in an attempt to give a reasonable, although approximate answer? It is but natural that the mathematician should attempt to obtain as much of such information as possible and use it in the evaluation of the various probabilities of existence. Thus for instance, if, in the Paradox of Bing, we had observed that the probability of survival for a forty-year-old person never had been below .75 and never above .95, it would be but reasonable to substitute those limits in their proper integrals in order to attain an approximate answer. To illustrate this somewhat subjective determination of an a posteriori probability, we take another example from the memoirs of Bing and Kroman.

*Example (24).*—A merchant receives a cargo of 100,000 pieces of fruit. If every single fruit is untainted, the value of the cargo may be put at 10,000 Kroner. On the other hand, any part of the cargo more or less tainted is considered worthless. The merchant has never before received a similar cargo and does not know how the fruit has been affected by travel. As samples, he has selected 30 pieces picked at random from the cargo and all samples proved to be fresh. He asks a mathematician what value he can put on the cargo.

If the mathematician uses the special formula (II), assuming an equal distribution of ignorance, therefore assuming that it is equally probable that for example none, 5,000 or all the individual pieces of fruit were untainted, the answer is:

$$10,000 \frac{\int_0^1 v^{31} dv}{\int_0^1 v^{30} dv} = 9687.5 \text{ Kroner.}$$

If we use the true rule, the a posteriori probability of the wholesomeness of the cargo is given by the integral:

$$\frac{\int_0^1 uv^{31} dv}{\int_0^1 uv^{30} dv}$$

where  $v$  is the general expression for a possible probability of wholesomeness between 0 and 1 and  $udv$  the corresponding probability of existence. Now if the mathematician has no complete information as to this particular function,  $u$ , it would be foolish of him to attempt a calculation, since the hypothesis of an equal probability of existence for all possible values of  $v$  evidently gives an arbitrary and perhaps a very erroneous result. On the other hand, the computer may possibly have access to some partial information. Perhaps the merchant has received fruit of a similar kind or heard about cargoes of this particular kind of fruit received by other dealers. If now the merchant were able to inform the computer that in a great number of similar cases the probability of wholesomeness had been between 0.9 and 1 with an approximately even distribution, while it never had been below 0.9, then nothing would hinder the mathematician to present the following computation:

$$\frac{\int_{0.9}^1 v^{31} dv}{\int_{0.9}^1 v^{30} dv} = 0.9726$$

and tell the merchant that on the basis of the information given 9,726 Kroner would be a fair price for the cargo.

This is really the point of view taken by the English mathematician, Professor Karl Pearson, one of the ablest writers on mathematical statistics of the present time, when he says: "I start, as most writers on mathematics have done, with 'the equal distribution of ignorance' or I assume the truth of Bayes's Theorem. I hold this theorem not as rigidly demonstrated, but I think with Edgeworth that the hypothesis of the equal distribution of ignorance is, within the limits of practical life, justified by our experience of statistical ratios, which are unknown, i. e., such ratios do not tend to cluster markedly round any particular point."

To sum up the above remarks: Theoretically Bayes's Rule is true. If we are able to enumerate and determine the probabilities of existence of the complexes of origin it will also give true results in practice. If we are justified in assuming the principle

of "insufficient reason" or "equal distribution of ignorance" as the basis for our calculations, formula (II) may be employed with exact results after a rigid enumeration of the complexes. If the principle of "cogent reason" is required as the basis, an exact computation is in general hopeless, and we can only after having obtained partial subjective information give an approximate answer.

With these remarks we shall conclude the elementary discussion of the merely theoretical part of the subject. The following chapters require in most cases a knowledge of the infinitesimal calculus, and many of the questions discussed above will appear in a new and instructive light by this treatment.

## CHAPTER VII.

### THE LAW OF LARGE NUMBERS.

51. **A Priori and Empirical Probabilities.**—In the previous chapters we limited ourselves to the discussion of such mathematical probabilities, where we, a priori, on account of our knowledge of the various domains or complexes of actions, were able to enumerate the respective favorable and unfavorable possibilities associated with the occurrence or non-occurrence of the event in question. "The real importance of the theory of probability in regard to mass phenomena consists, however, in determining the mathematical relations of the various probabilities not in a deductive, but in an empirical manner—without an a priori exhaustive knowledge of the mutual relations and actions between cause and effect—by means of statistical enumeration of the frequency of the observed event. The conception of a probability finds its justification in the close relation between the *mathematical probabilities* and *relative frequencies* as determined in a purely empirical way. This relation is established by means of the famous Law of Large Numbers" (A. A. Tschuprow).

To return to our original definition of a mathematical probability as the ratio of the favorable to the coördinated equally possible cases, we first notice that this definition is wholly arbitrary like many mathematical definitions. The contention of Stuart Mill that every definition contains an axiom is rather far stretched. In mathematics a definition does not necessarily need to be metaphysical. A striking example is offered in mechanics by the definitions of force as given by Lagrange and Kirchhoff. What is force? "Force," Lagrange says, "is a cause which tends to produce motion." Kirchhoff on the other hand tells us that force is the product of mass and acceleration. Lagrange's definition is wholly metaphysical. Whenever a definition is to be of use in a purely exact science such as mathematics, it must teach us how to measure the particular phenomena which we are investigating. Thus, to quote Poincaré,

"it is not necessary that the definition tells us what force really is, whether it is a cause or the effect of motion."

An analogous case is offered in the criticism of a mathematical probability as defined by Laplace, and the attempts to place the whole theory of probabilities on a purely empirical basis by Stuart Mill, Venn and Chrystal. These writers contend "that probability is not an attribute of any particular event happening on any particular occasion. Unless an event can happen, or be conceived to happen a great many times, there is no sense in speaking of its probability." The whole attack is directed against the definition of a mathematical probability in a *single trial* which definition, evidently by the empiricists, is regarded as having no sense. The word "sense" must evidently be considered as having a purely metaphysical meaning. In the same manner Kirchhoff's definition might be dismissed as having no sense, since it would seem as difficult to conceive force as a purely mathematical product of two factors, mass and acceleration, as it is to conceive the definition of a mathematical probability as a ratio.

The metaphysical trend of thought of the above writers is shown in their various definitions of the probability of an event. Mill defines it merely as the relative frequency of happenings inside a large number of trials, and Venn gives a similar definition, while Chrystal gives the following:

"If, on taking any very large number  $N$  out of a series of cases in which an event,  $E$ , is in question,  $E$  happens on  $pN$  occasions, the probability of the event,  $E$ , is said to be  $p$ ."

Let us, for a moment, look more closely into these statements. Any definition, if it bears its name rightly, must mean the same to all persons. Now, as a matter of fact, the vagueness in a half metaphorical term like "any very large number" illustrates its weakness. The question immediately confronts us "what is a very large number?" Is it 100, 1,000 or perhaps 1,000,000?

A fixed universal standard for the value of  $N$  seems out of the question and the definition—although perhaps readily grasped in a "general way"—can hardly be said to be happily chosen.

Another, and perfectly rigorous definition, is the following one given by the Danish astronomer and actuary, T. N. Thiele.

Thiele tells us that "common usage" has assigned the word probability as the name "for the limiting value of the relative frequency of an event, when the number of observations (trials), under which the event happens, approach infinity as a limit." A similar definition is later on given by the American actuary R. Henderson, who says: "The numerical measure which has been universally adopted for the probability of an event under given circumstances is the ultimate value, as the number of cases is indefinitely increased, of the ratio of the number of times the event happens under those circumstances to the total possible number of times." There is nothing ambiguous or vague in these definitions. Infinity, taken in a purely quantitative sense, has a perfectly uniform meaning in mathematics. The new definition differs, however, radically from our customary definition of a mathematical *a priori* probability. We cannot, therefore, agree with Mr. Henderson when he continues "the measure there given has been universally adopted and this holds true in spite of the fact that the rule has been stated in ways which on their face differ widely from that above given. The one most commonly given is that if an event can happen in  $a$  ways and fail in  $b$  ways all of which are equally likely, the probability of the event is the ratio of  $a$  to the sum of  $a$  and  $b$ . It is readily seen that if we read into this statement the meaning of the words "equally likely," this measure, so far as it goes, reduces to a particular case of that given above."

In order to investigate this statement somewhat more closely, let us try to measure the probability of throwing head with an ordinary coin by both our old definition of a mathematical probability and the definition by Mr. Henderson of what we shall term an empirical probability. Denoting the first kind of probability by  $P(E)$  and the second by  $P'(E)$  we have in ordinary symbols

$$P(E) = \frac{1}{2}$$

$$P'(E) = \lim_{v \rightarrow \infty} F(E, v)$$

where the symbol  $F(E, v)$  denotes the relative frequency of the event,  $E$ , in  $v$  total trials. No *a priori* knowledge will tell us offhand if  $P'(E)$  will approach  $\frac{1}{2}$  as its ultimate value. The

two methods are radically different. By the first method the determination of the numerical measure of a probability depends simply on our ability to judge and segregate the equally possible cases into cases favorable and unfavorable to the event  $E$ . By the second method the determination of the probability depends, not alone on the segregation and consequent enumeration of the favorable from the total cases, but chiefly on the extent of our observations or trials on the event in question.

**52. Extent and Usage of Both Methods.**—Before entering into a more detailed discussion of the actual quantitative comparison of the two methods, it might be of use to compare their various extent of usage. In this respect the empirical method is vastly superior to the *a priori*. A rigorous application of the *a priori* method, as far as concrete problems go, is limited to simple games of chance. As soon as we begin to tackle sociological or economical practical problems it leaves us in a helpless state. If we were to ask about the probability that a certain person forty years of age would die inside a year, it would be of little use to try to determine this in an *a priori* manner. Even a purely deductive process, as illustrated by Bayes's Rule in the earlier chapters, leads to paradoxical results. Our *a priori* knowledge of the complexes of causes governing death or survival is so incomplete that even a qualitative—not to speak of a quantitative—judgment is out of the question. The empirical method shows us at least a way to obtain a measure for the probability of the event in question. By observing during a period of a year an infinite number of forty-year-old persons of whom, after an exhaustive qualitative investigation, we are led to believe that their present conditions as far as health, social occupation, environments, etc., are concerned are equally similar, we may by an enumeration of those who died during the year obtain the desired ratio as defined by  $P'(E)$ . Of course, observation an infinite number is practically impossible. An approximate ratio may be formed by taking a finite, but a large, number of cases under observation. But how large a number? This very question leads straightforward to another problem, namely the quantitative determination of the range of variance between the approximate ratio and the ideal ultimate ratio as defined by

the relation

$$P'(E) = \lim_{v \rightarrow \infty} F(E, v).$$

Since it is impossible to make an infinite number of observations we cannot find the exact value of the range of such variations. But we may, however, determine the probability that this range does not exceed a certain fixed quantity, say  $\lambda$ , in absolute magnitude. Stated in compact form our problem reduces to the following form: To determine the probability of the existence of the following inequality:

$$\left| \lim_{s \rightarrow \infty} F(E, v) - \frac{\alpha}{s} \right| \leq \lambda$$

where both  $\alpha$  and  $s$  are finite numbers. This, to a certain extent, contains in a nut shell some of the most important problems in probabilities.

The above problem may be solved in two distinct ways. The first, and perhaps the most logical way, is by a direct process. This is the method followed by T. N. Thiele in his "*Almindelig lagttagelseslære*,"<sup>1</sup> published in Copenhagen, 1889, a most original work, which moves along wholly novel lines. Thiele distinguishes between (1) Actual observation series as recorded from observation, in other words statistical data. (2) Theoretical observation series giving the conclusions as to the outcome of future observations and (3) Methodical laws of series where the number of observations is increased indefinitely. By such a process, purely a theory of observations, the whole theory of probability becomes of secondary importance and rests wholly upon the theory of observed series, a fact thoroughly emphasized by Thiele himself. When the author first, in the closing chapters of his book, makes use of the word probability it is only because "common usage" has assigned this word as the name for the ultimate frequency ratio designated by our symbol  $\lim_{v \rightarrow \infty} F(E, v)$ .

The problem may, however, be solved in an indirect way, which is the one I shall adopt. This method, as first consistently deduced by Laplace, has for its basis our original definition of a mathematical a priori probability and may be briefly sketched as follows: We first of all postulate the existence of an a priori

<sup>1</sup> English edition, "Theory of Observations," London, 1905.

probability as defined, although its actual determination, by a priori knowledge, is impossible except in a few cases, as, for instance, simple games of chance, drawing balls from urns, etc. Denoting such a probability by  $P(E)$ , or  $p$ , we next ask, What will be the expected number, say  $\alpha$ , of actual happenings of the event,  $E$ , expressed in terms of  $s$  and  $p$ , when we make  $s$  consecutive trials instead of a single trial, and what will be the number of happenings of  $E$  when  $s$  approaches infinity as its ultimate value? If such a relation is found between  $p$ ,  $\alpha$  and  $s$ , where  $p$  is the unknown quantity, we have also found a means of determining the value of  $p$  in known quantities. Our next question is—What is the probability that the absolute value of the difference between  $p$  and the relative frequency of the event as expressed by the ratio of  $\alpha$  to  $s$  does not exceed a previously assigned quantity? Or the probability that

$$\left| p - \frac{\alpha}{s} \right| \leq \lambda?$$

Now, as the reader will see later, we shall prove that

$$\lim_{v \rightarrow \infty} F(E, v) = P(E) = p.$$

It must, however, be remembered that this result is reached by a mathematical deduction, based upon the postulate of mathematical probabilities, and not in the manner as suggested in the above statement by Mr. Henderson.

It is only after having established such purely quantitative relations that we are entitled to extend the laws of mathematical probabilities as deduced in the earlier chapters to other problems than the simple problems of games of chance.

**53. Average a Priori Probabilities.**—In the previous paragraphs of this chapter, another important matter is to be noted, namely the assumption that the complex of causes producing the event in question remains constant during the repeated trials (observations), or, stated in other words the mathematical a priori probability remains constant. Under this limitation the extension of the laws of mathematical probabilities would have but a very limited practical application. In all statistical mass phenomena such an ideal state of affairs is rather a very

rare exception. If we consider an ordinary mortality investigation we know with absolute certainty that no two persons are identically alike as far as health, occupation, environment and numerous other things are concerned. Thus the postulated mathematical probability for death or survival during a whole calendar year will in general be different for each person. We may, however, conceive an average probability of survival for a full year defined by the relation

$$p_0 = \frac{p_1 + p_2 + p_3 + \cdots + p_s}{s} = \frac{\Sigma p}{s},$$

where  $p_1, p_2, p_3, \dots$  are the postulated probabilities of each individual under observation. Our task is now to find:

1. An algebraic relation between the average probability as defined above, the absolute frequency  $\alpha$  and the total number of observations (trials)  $s$ ,
2. The same relation when  $s$  approaches  $\alpha$  as its ultimate value,
3. The probability of the existence of the inequality,

$$\left| p_0 - \frac{\alpha}{s} \right| \leq \lambda,$$

where  $\alpha$  denotes the absolute frequency of the occurrence of the event,  $s$  the total number of observations (trials) and  $\lambda$  an arbitrary constant.

**54. The Theory of Dispersion.**—As we mentioned before the empirical ratio  $\alpha/s$  represents only an approximation of the ideal ultimate value of  $\lim_{v \rightarrow \infty} F(E, v)$ . If we now make a series of observations (trials) on the occurrence of a certain event  $E$ , such that instead of a single set of observations of  $s$  individual observations we take  $N$  such sets, we shall have  $N$  relative frequency ratios:

$$\frac{\alpha_1}{s}, \frac{\alpha_2}{s}, \frac{\alpha_3}{s}, \dots, \frac{\alpha_N}{s}.$$

Since the ratios are approximations only of the ultimate ratio they will in general exhibit discrepancies as to their numerical values and may be regarded as  $N$  different empirical approximations. The question now arises how these various empirical ratios group themselves around the value of  $\lim_{v \rightarrow \infty} F(E, v)$ . The dis-

tribution of the empirical ratios around the ultimate ratio is by Lexis called "dispersion."

#### 55. Historical Development of the Law of Large Numbers.—

The first mathematician to investigate the problems we have roughly outlined in the previous paragraphs was the renowned Jacob Bernoulli in the classic, "*Ars Conjectandi*," which rightly may be classified as one of the most important contributions on the subject. Bernoulli's researches culminate in the theorem which bears his name and forms the corner-stone of modern mathematical statistics. That Bernoulli fully realized the great practical importance of these investigations is proven by the heading of the fourth part of his book which runs as follows: "*Artis Conjectandi Pars Quarta, tradens usum et applicationem præcedentis doctrinæ in civilibus et œconomicis.*" It is also here that we first encounter the terms "a priori" and "a posteriori" probabilities. Bernoulli's researches were limited to such cases where the a priori probabilities remained constant during the series or the whole sets of series of observations. Poisson, a French mathematician, treated later in a series of memoirs the more general case where the a priori probabilities varied with each individual trial. He also introduced the technical term, "Law of Large Numbers" ("*Loi des Grand Nombres*"). Finally Lexis through the publication in 1877 of his brochure, "*Zur Theorie der Massenerscheinungen der menschlichen Gesellschaft*," treated the dispersion theory and forged the closing link of the chain connecting the theory of a priori probabilities and empirical frequency ratios. Of late years the Russian mathematician, Tchebycheff, the Scandinavian statisticians, Westergaard and Charlier, and the Italian scholar, Pizetti, have contributed several important papers. It is on the basis of these papers that the following mathematical treatment is founded. In certain cases, however, we shall not attempt to enter too deeply into the theory of certain definite integrals, which is essential for a rigorous mathematical analysis, but which also requires an extensive mathematical knowledge which many of my readers, perhaps, do not possess. To readers interested in the analysis of the various integrals we may refer to the original works of Czuber and Charlier.

## CHAPTER VIII.

### INTRODUCTORY FORMULAS FROM THE INFINITESIMAL CALCULUS.

**56. Special Integrals.**—In the following chapters we shall attempt to investigate the theory of probabilities from the standpoint of the calculus. Although a knowledge of the elements of this branch of mathematics is presupposed to be possessed by the student, we shall for the sake of convenience briefly review and demonstrate a few formulas from the higher analysis of which we shall make frequent use in the following paragraphs. All such formulas have been given in the elementary instruction of the calculus, and only such readers who do not have this particular branch of mathematics fresh in memory from their school days need pay any serious attention to the first few paragraphs.

**57. Wallis's Expression for  $\pi$  as an Infinite Product.**—We wish first of all to determine the value of the definite integral:

$$J_n = \int_0^{\pi/2} \sin^n x dx, \quad (1)$$

under the assumption that  $n$  is a positive integral number. This integral is geometrically equal to the area between the  $x$  axis, the axis of  $y$ , the ordinate corresponding to the abscissa  $\frac{1}{2}\pi$  and the graph of the function  $y = \sin^n x$ . Letting  $u' = D_x u = \sin x$ ,  $v = \sin^{n-1} x$ , we get by partial integration:

$$J_n = -\cos x \sin^{n-1} x \Big|_0^{\pi/2} + \int_0^{\pi/2} \cos x (n-1) \sin^{n-2} x \cos x dx. \quad (2)$$

If we substitute the upper and lower limits in the first term on the right hand side of the above expression for  $J_n$  this term reduces to 0, assuming  $n > 1$ . Thus we have:

$$J_n = (n-1) \int_0^{\pi/2} \sin^{n-2} x \cdot \cos^2 x dx.$$

Putting  $\cos^2 x = 1 - \sin^2 x$ , we get:

$$J_n = (n-1) \int_0^{\pi/2} \sin^{n-2} x dx - (n-1) \int_0^{\pi/2} \sin^n x dx. \quad (3)$$

The last integral is, however, equal to  $J_n$  and the first integral is, following the notation from (1), equal to  $J_{n-2}$ . We shall therefore have:

$$J_n + (n-1)J_n = (n-1)J_{n-2},$$

or

$$nJ_n = (n-1)J_{n-2}. \quad (4)$$

Replacing  $n$  by  $n-1$ ,  $n-2$ ,  $n-3$ ,  $\dots$  successively we get:

$$\begin{aligned} nJ_n &= (n-1)J_{n-2}, \\ (n-1)J_{n-1} &= (n-2)J_{n-3}, \\ (n-2)J_{n-2} &= (n-3)J_{n-4}, \\ &\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \end{aligned}$$

According as  $n$  is even or uneven we shall have one of the following equations at the bottom of the recursion formula:

$$J_0 = \int_0^{\pi/2} \sin^0 x dx = \int_0^{\pi/2} dx = \frac{1}{2}\pi,$$

or

$$J_1 = \int_0^{\pi/2} \sin x dx = -\cos x \Big|_0^{\pi/2} = 1. \quad (5)$$

If, for even values of  $n$ , we let  $n = 2m$ , and, for uneven values,  $n = 2m-1$ , we get finally the following recursion formulas:

$$\begin{aligned} 2mJ_{2m} &= (2m-1)J_{2m-2}, & (2m-1)J_{2m-1} &= (2m-2)J_{2m-3}, \\ (2m-2)J_{2m-2} &= (2m-3)J_{2m-4}, & (2m-3)J_{2m-3} &= (2m-4)J_{2m-5}, \\ &\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots & \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ 2J_2 &= 1 \cdot \frac{1}{2}\pi, & 3J_3 &= 2 \times 1. \end{aligned}$$

Successive multiplication of the above equations gives us finally:

$$\begin{aligned} J_{2m} &= \frac{(2m-1)(2m-3)\dots 1}{2m(2m-2)\dots 2} \times \frac{\pi}{2}, \\ J_{2m-1} &= \frac{(2m-2)(2m-4)\dots 2}{(2m-1)(2m-3)\dots 3}. \end{aligned} \quad (6)$$

We may now draw some very interesting conclusions from the

Thiele tells us that "common usage" has assigned the word probability as the name "for the limiting value of the relative frequency of an event, when the number of observations (trials), under which the event happens, approach infinity as a limit." A similar definition is later on given by the American actuary R. Henderson, who says: "The numerical measure which has been universally adopted for the probability of an event under given circumstances is the ultimate value, as the number of cases is indefinitely increased, of the ratio of the number of times the event happens under those circumstances to the total possible number of times." There is nothing ambiguous or vague in these definitions. Infinity, taken in a purely quantitative sense, has a perfectly uniform meaning in mathematics. The new definition differs, however, radically from our customary definition of a mathematical a priori probability. We cannot, therefore, agree with Mr. Henderson when he continues "the measure there given has been universally adopted and this holds true in spite of the fact that the rule has been stated in ways which on their face differ widely from that above given. The one most commonly given is that if an event can happen in  $a$  ways and fail in  $b$  ways all of which are equally likely, the probability of the event is the ratio of  $a$  to the sum of  $a$  and  $b$ . It is readily seen that if we read into this statement the meaning of the words "equally likely," this measure, so far as it goes, reduces to a particular case of that given above."

In order to investigate this statement somewhat more closely, let us try to measure the probability of throwing head with an ordinary coin by both our old definition of a mathematical probability and the definition by Mr. Henderson of what we shall term an empirical probability. Denoting the first kind of probability by  $P(E)$  and the second by  $P'(E)$  we have in ordinary symbols

$$P(E) = \frac{1}{2}$$

$$P'(E) = \lim_{v \rightarrow \infty} F(E, v)$$

where the symbol  $F(E, v)$  denotes the relative frequency of the event,  $E$ , in  $v$  total trials. No a priori knowledge will tell us offhand if  $P'(E)$  will approach  $\frac{1}{2}$  as its ultimate value. The

two methods are radically different. By the first method the determination of the numerical measure of a probability depends simply on our ability to judge and segregate the equally possible cases into cases favorable and unfavorable to the event  $E$ . By the second method the determination of the probability depends, not alone on the segregation and consequent enumeration of the favorable from the total cases, but chiefly on the extent of our observations or trials on the event in question.

**52. Extent and Usage of Both Methods.**—Before entering into a more detailed discussion of the actual quantitative comparison of the two methods, it might be of use to compare their various extent of usage. In this respect the empirical method is vastly superior to the *a priori*. A rigorous application of the *a priori* method, as far as concrete problems go, is limited to simple games of chance. As soon as we begin to tackle sociological or economical practical problems it leaves us in a helpless state. If we were to ask about the probability that a certain person forty years of age would die inside a year, it would be of little use to try to determine this in an *a priori* manner. Even a purely deductive process, as illustrated by Bayes's Rule in the earlier chapters, leads to paradoxical results. Our *a priori* knowledge of the complexes of causes governing death or survival is so incomplete that even a qualitative—not to speak of a quantitative—judgment is out of the question. The empirical method shows us at least a way to obtain a measure for the probability of the event in question. By observing during a period of a year an infinite number of forty-year-old persons of whom, after an exhaustive qualitative investigation, we are led to believe that their present conditions as far as health, social occupation, environments, etc., are concerned are equally similar, we may by an enumeration of those who died during the year obtain the desired ratio as defined by  $P'(E)$ . Of course, observation an infinite number is practically impossible. An approximate ratio may be formed by taking a finite, but a large, number of cases under observation. But how large a number? This very question leads straightforward to another problem, namely the quantitative determination of the range of variance between the approximate ratio and the ideal ultimate ratio as defined by

the relation

$$P'(E) = \lim_{v \rightarrow \infty} F(E, v).$$

Since it is impossible to make an infinite number of observations we cannot find the exact value of the range of such variations. But we may, however, determine the probability that this range does not exceed a certain fixed quantity, say  $\lambda$ , in absolute magnitude. Stated in compact form our problem reduces to the following form: To determine the probability of the existence of the following inequality:

$$\left| \lim_{s \rightarrow \infty} F(E, v) - \frac{\alpha}{s} \right| \leq \lambda$$

where both  $\alpha$  and  $s$  are finite numbers. This, to a certain extent, contains in a nut shell some of the most important problems in probabilities.

The above problem may be solved in two distinct ways. The first, and perhaps the most logical way, is by a direct process. This is the method followed by T. N. Thiele in his "*Almindelig Iagttagelseslære*,"<sup>1</sup> published in Copenhagen, 1889, a most original work, which moves along wholly novel lines. Thiele distinguishes between (1) Actual observation series as recorded from observation, in other words statistical data. (2) Theoretical observation series giving the conclusions as to the outcome of future observations and (3) Methodical laws of series where the number of observations is increased indefinitely. By such a process, purely a theory of observations, the whole theory of probability becomes of secondary importance and rests wholly upon the theory of observed series, a fact thoroughly emphasized by Thiele himself. When the author first, in the closing chapters of his book, makes use of the word probability it is only because "common usage" has assigned this word as the name for the ultimate frequency ratio designated by our symbol  $\lim_{v \rightarrow \infty} F(E, v)$ .

The problem may, however, be solved in an indirect way, which is the one I shall adopt. This method, as first consistently deduced by Laplace, has for its basis our original definition of a mathematical a priori probability and may be briefly sketched as follows: We first of all postulate the existence of an a priori

<sup>1</sup> English edition, "Theory of Observations," London, 1905.

probability as defined, although its actual determination, by a priori knowledge, is impossible except in a few cases, as, for instance, simple games of chance, drawing balls from urns, etc. Denoting such a probability by  $P(E)$ , or  $p$ , we next ask, What will be the expected number, say  $\alpha$ , of actual happenings of the event,  $E$ , expressed in terms of  $s$  and  $p$ , when we make  $s$  consecutive trials instead of a single trial, and what will be the number of happenings of  $E$  when  $s$  approaches infinity as its ultimate value? If such a relation is found between  $p$ ,  $\alpha$  and  $s$ , where  $p$  is the unknown quantity, we have also found a means of determining the value of  $p$  in known quantities. Our next question is—What is the probability that the absolute value of the difference between  $p$  and the relative frequency of the event as expressed by the ratio of  $\alpha$  to  $s$  does not exceed a previously assigned quantity? Or the probability that

$$\left| p - \frac{\alpha}{s} \right| \leq \lambda?$$

Now, as the reader will see later, we shall prove that

$$\lim_{s \rightarrow \infty} F(E, s) = P(E) = p.$$

It must, however, be remembered that this result is reached by a mathematical deduction, based upon the postulate of mathematical probabilities, and not in the manner as suggested in the above statement by Mr. Henderson.

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## CHAPTER IX.

### LAW OF LARGE NUMBERS. MATHEMATICAL DEDUCTION.

**59. Repeated Trials.**—Let us consider a general domain of action wherein the determining causes remain constant and produce either one or the other of the opposite and mutually exclusive events,  $E$  and  $\bar{E}$ , with the respective a priori probabilities  $p$  and  $q$  ( $q = 1 - p$ ) in a single trial. The trial (observation) will, however, be repeated  $s$  times with the explicit assumption that the outward conditions influencing the different trials remain unaltered during each observation. The simplest example of observations of this kind is offered by repeated drawings of balls from an urn containing white and black balls only, and where the ball is put back in the urn and mixed thoroughly with the rest before the next drawing takes place. We keep now a record of the repetitions of the opposite events,  $E$  and  $\bar{E}$  during the  $s$  trials, irrespective of the order in which these two events may happen. This record must necessarily be of one of the following forms:

|     |         |         |        |           |          |
|-----|---------|---------|--------|-----------|----------|
| $E$ | happens | $s$     | times, | $\bar{E}$ | 0 times, |
| $E$ | "       | $s - 1$ | "      | $\bar{E}$ | 1 "      |
| $E$ | "       | $s - 2$ | "      | $\bar{E}$ | 2 "      |
| .   | .       | .       | .      | .         | .        |
| .   | .       | .       | .      | .         | .        |
| $E$ | "       | 0       | "      | $\bar{E}$ | $s$ "    |

In Chapter IV, Example 17, we showed that the probabilities of the above combinations of the two events,  $E$  and  $\bar{E}$ , were determined by the expansion of the binomial

$$(p + q)^s.$$

The general term

$$\frac{s!}{\alpha! \beta!} p^\alpha q^\beta \quad (\alpha + \beta = s)$$

is the probability  $P(E^\alpha \bar{E}^\beta)$  that  $E$  will happen  $\alpha$  and  $\bar{E}$   $\beta$  times in the  $s$  total trials. Each separate term of the binomial expansion of  $(p + q)^s$ , represents the probability of the happening of the two events in the order given in the above scheme.

**60. Most Probable Value.**—In dealing with these various terms, it has usually been the custom of the English and French mathematicians as well as many German scholars to pay particular attention to a special term, the maximum term, which generally is known as the “most probable value” or the “mode.” Russian and Scandinavian writers and the followers of the Lexis statistical school of Germany have preferred to make another quantity known as the “probable” or “expected value,” the nucleus of their investigations. Although it is our intention to follow the latter method, we shall discuss first, briefly, the most probable value. Two questions are then of special interest to us:

- (1) What particular event is most probable to happen?
- (2) What is the probability that an event will occur whose probability does not differ from that of the most probable event by more than a previously fixed quantity?

Neither of the two questions offers any particular principal difficulties from a theoretical point of view. When regarding the probability  $P(E^\alpha \bar{E}^\beta)$ , which we shall denote by  $T$ , as a function of the variable quantity,  $\alpha$ ,  $T$  evidently will reach a maximum value for a certain value of  $\alpha$ , ( $\beta = s - \alpha$ ), and we need only determine the greatest term in the above binomial expansion.

In order to answer the second question we have only to pick out all the terms which are situated between the two fixed limits. Their sum is then the probability that those two limits are not exceeded.

**61. Simple Numerical Examples.**—When  $s$  is a comparatively small number the actual expansion may be performed by simple arithmetic. We shall, for the benefit of the student, give a simple example of this kind.

A pair of dice is thrown 4 times in succession, to investigate the chance of throwing doublets.

In a single throw the probability of getting a doublet is  $p = \frac{1}{6}$ ;  $(q = \frac{5}{6})$ . Expanding  $(\frac{1}{6} + \frac{5}{6})^4$  by means of the binomial theorem we get  $(\frac{1}{6})^4 + 4(\frac{1}{6})^3(\frac{5}{6}) + 6(\frac{1}{6})^2(\frac{5}{6})^2 + 4(\frac{1}{6})(\frac{5}{6})^3 + (\frac{5}{6})^4$ . Each of the above terms represents the probability of the occurrence of the various combinations of doublets ( $E$ ) and non-doublets ( $\bar{E}$ ), and it is readily seen that the event of 1 doublet and 3 non-doublets, represented by the term  $4(\frac{1}{6})(\frac{5}{6})^3 = .3858$ , has the greatest probability. In other words it is the *most probable* event.

Let us next repeat the trial 12 times instead of 4. The 13 possible probabilities for the various combinations of doublets and non-doublets will then be expressed by the respective terms in the expression

$$(\frac{1}{6} + \frac{5}{6})^{12}.$$

The 13 members have as their common denominator the quantity 2,176,782,336 and as numerators the following quantities: 1, 60, 1,650, 27,500, 309,375, 2,475,000, 14,437,500, 61,875,000, 193,359,375, 429,687,500, 644,531,250, 585,937,500, 244,140,625, which now shows that the most probable combination is the one of 2 doublets and 10 non-doublets, having a numerical value equal to .2961.

A further comparison will show that the most probable event in the second series had the probability .2961, whereas .3858 was its value in the first series. In other words, the probability decreases when the trials (observations) are increased. This is due to the fact that the total number of possible cases becomes large with the increase of experiments.

Another question which presents itself, in this connection, is the following: What is the probability that an event will occur

whose probability does not differ from the most probable value by more than a previously fixed quantity? Let us suppose we were asked to determine the probability that a doublet does not occur oftener than 5 times and not less than 1 time in 12 trials. This probability is found by adding the numerical values of the probabilities as given in the binomial expansion from the term containing  $p = \frac{1}{6}$  to the power 6, to  $p$  to the first power or

$$\begin{array}{r} 14,437,500 + 6,187,500 + 193,359,375 + 429,687,500 \\ + 644,531,250 + 585,937,500 \\ \hline 2,176,782,336 \end{array}$$

## 62. The Most Probable Value in a Series of Repeated Trials.

—In the examples just given we determined the probability for the happening of the most probable event in a series of  $s$  observations by a direct expansion of the binomial  $(p+q)^s$ . This may be done whenever  $s$  is a comparatively small number. But, when  $s$  takes on large values, this method becomes impracticable, not to say impossible. Suppose that  $s = 1,400$ , then the actual straightforward expansion  $(p+q)^{1400}$  would require a tremendous work of calculation which no practical computer would be willing to undertake. We must therefore in some way or other seek a method of approximation by which this labor of calculation may be avoided and try to find an approximate formula by which we are able to express the maximum term in a simple manner, involving little computation and at the same time yielding results close enough for practical as well as theoretical purposes. Jacob Bernoulli in his famous treatise “*Ars Conjectandi*” was the first mathematician to solve this problem. Bernoulli also gave an expression for the probability that the departure from the most probable value should not exceed previously fixed limits. The method, however, was very laborious and the final form was first reached by Laplace in “*Théorie des Probabilités*.”

We saw before in Chapter IV that the general term

$$T = \frac{s!}{\alpha! \beta!} p^\alpha q^\beta \quad (\alpha + \beta = s)$$

in the binomial expansion  $(p + q)^s$  represented the probability that an event,  $E$ , will happen  $\alpha$  times and fail  $\beta$  times in  $s$  trials, where  $p$  and  $q$  were the respective probabilities for success and failure in a single trial. The exponent  $\alpha$  may here take all positive integral values in the interval  $(0, s)$ , including both limits. The question now arises, which particular value of  $\alpha$ , say  $\alpha_n$ , will make the above quantity a maximum term in the expansion of the binomial? If  $\alpha_n$  really is this particular value, then it must satisfy the following inequalities:

$$\begin{aligned} \frac{s!}{(\alpha_n + 1)!(\beta_n - 1)!} p^{\alpha_n + 1} q^{\beta_n - 1} &\leq \frac{s!}{\alpha_n! \beta_n!} p^{\alpha_n} q^{\beta_n} \\ &\geq \frac{s!}{(\alpha_n - 1)!(\beta_n + 1)!} p^{\alpha_n - 1} q^{\beta_n + 1}. \end{aligned} \quad \begin{array}{l} \text{(I)} \\ \text{(II)} \\ \text{(III)} \end{array}$$

Dividing (II) by (III) and (II) by (I) we obtain the following inequalities:

$$\frac{\beta_n + 1}{\alpha_n} \frac{p}{q} \geq 1 \text{ and } \frac{\alpha_n + 1}{\beta_n} \frac{q}{p} \geq 1,$$

which also may be written

$$(\beta_n + 1)p \geq q\alpha_n \text{ and } (\alpha_n + 1)q \geq \beta_n p.$$

The following reductions are self evident:

$$(s - \alpha_n + 1)p \geq \alpha_n(1 - p) \text{ or } sp + p \geq \alpha_n,$$

and

$$(\alpha_n + 1)q \geq (s - \alpha_n)p \text{ or } \alpha_n q + \alpha_n p \geq sp - q \text{ or } \alpha_n \geq sp - q.$$

From which we see that  $\alpha_n$  satisfies the following relation:

$$ps - q \leq \alpha_n \leq ps + p.$$

Since  $p + q = 1$ , we notice that  $\alpha_n$  is enclosed between two limits whose difference in absolute magnitude equals unity. The whole interval in which  $\alpha_n$  is situated being equal to unity, and since  $\alpha_n$  must be an integral number, this particular  $\alpha_n$  is determined uniquely as an integral positive number when both  $ps - q$  and  $ps + p$  are fractional quantities. If  $ps - q$  is an integral number  $ps + p$  will also be integral, and  $\alpha_n$  had to be a

fractional number in order to satisfy the above inequality. Since by the nature of the problem  $\alpha_n$  can take positive integral values only, the binomial expansion of  $(p+q)^s$  must have two terms which are greater than any of the rest. Dividing both sides of the inequality by  $s$ , we shall have

$$p - \frac{q}{s} < \frac{\alpha_n}{s} < p + \frac{p}{s} \text{ or } q + \frac{q}{s} > \frac{\beta_n}{s} \text{ and } p + \frac{p}{s} > \frac{\alpha_n}{s}.$$

Since both  $p$  and  $q$  are proper fractions, both  $p/s$  and  $q/s$  are less than  $1/s$ . We may therefore safely assume that the highest possible difference between the two quotients  $\alpha_n/s$  and  $\beta_n/s$  and the probabilities  $p$  and  $q$  will never exceed  $1/s$ . Now if  $s$  is a very large number this quantity may be neglected, and we may therefore write  $ps = \alpha_n$  and  $qs = \beta_n$ .

Substituting these values in our original expression for the general term of the binomial expansion we get as the maximum number:

$$T_m = \frac{s!}{(sp)!(sq)!} p^{sp} q^{sq}.$$

**63. Approximate Calculation of the Maximum Term,  $T_m$ .—**When the trials are repeated a large number of times the straightforward calculation of the maximum term becomes very laborious. The only table facilitating an exact computation is in a work "Tabularum ad Faciliorem et Breviorem Probabilitatis Computationem Utilium, Enneas," by the Danish mathematician, C. F. Degen. This table, which was published in 1824, gives the logarithms to twelve places for all values of  $n!$  from  $n = 1$  to  $n = 1,200$ . Degen's table is, however, not easily obtained, and even if it were, it would be of little or no value for factorials above 1,200!. Our only resort is therefore to find an approximate expression for the above value of  $n!$ . This is most conveniently done by making use of Stirling's formula for factorials of high orders. We have

$$s! = s^{s+1/2} e^{-s} \sqrt{2\pi},$$

$$(sp)! = (sp)^{sp+1/2} e^{-sp} \sqrt{2\pi},$$

$$(sq)! = (sq)^{sq+1/2} e^{-sq} \sqrt{2\pi}.$$

Substituting the above values in the expression  $s!/((sp)!(sq)!)$  we get

$$\frac{1}{p^{sp+1/2}q^{sq+1/2}\sqrt{2\pi s}}.$$

Hence we have

$$T_m = \frac{p^{sp}q^{sq}}{p^{sp+1/2}q^{sq+1/2}\sqrt{2\pi s}},$$

which reduces to

$$T_m = \frac{1}{\sqrt{2\pi spq}}$$

as an approximate value for the maximum term.

*Tchebycheff's Theorems.*—Despite all that has been said about the most probable value, its use is somewhat limited, and it might well, without harm, be left out of the whole theory of probabilities. Just because an event is the most probable it does by no means follow it is a very probable event. In fact the expression  $(\sqrt{2\pi spq})^{-1}$  which for large values of  $s$  converges towards zero shows that the most probable event in reality is a very improbable event. This statement may seem a little paradoxical; but it is easily understood by realizing that the most probable event is only a probability for a possible combination among a large number of equally possible combinations of a different order.

Instead of finding the most probable event it is more important in practical calculations to determine the average number or mean value of the absolute frequencies of successes. In Chapter V we pointed out the close relation between a mathematical expectation and the mean value of a variable. This relation is used by the Russian mathematician, Tchebycheff, as the basis of some very general and far-reaching theorems in probabilities, by means of which the Law of Large Numbers may be established in an elegant and elementary manner.

**64. Expected or Probable Value.**—In Chapter V we defined the product of a certain sum,  $s$ , and the probability of winning such a sum as the mathematical expectation of  $s$ . It is, however, not necessary to associate the happening of the event with a monetary gain or loss, in fact it serves often to confuse the reader and we may generalize the definition as follows. If  $a$

variable  $\alpha_i$  may assume any of the values  $\alpha_1, \alpha_2, \alpha_3 \dots \alpha_s$  each with a respective probability of existence  $\varphi(\alpha_i)$  ( $i = 1, 2 \dots s$ ) and such that  $\Sigma \varphi(\alpha_i) = 1$ , then we define:

$$\Sigma \alpha_i \varphi(\alpha_i) = e(\alpha_i)$$

as the expected value of  $\alpha_i$ .

Some writers use also the term probable value instead of expected value. In other words the expected value of a variable quantity,  $\alpha$ , which may assume any one of the values  $\alpha_1, \alpha_2 \dots \alpha_s$ , is the sum of the products of each individual value of the variable and the corresponding probability of existence of such value.

Suppose we now have two opposite and complementary events  $E$  and  $\bar{E}$  for which the probabilities of happening in a single trial are equal to  $p$  and  $q = 1 - p$  respectively. When the trials are repeated  $s$  times the probabilities of  $E$  happening  $s$  times,  $\bar{E}$  no times, of  $E$  happening  $s - 1$  and  $\bar{E}$  once, of  $E$   $s - 2$  and  $\bar{E}$  2 times and so on, may be expressed by the individual terms of the expansion:

$$(p + q)^s,$$

where the general term expressing the occurrence of  $E$   $\alpha$  times and of  $\bar{E}$  ( $s - \alpha$ ) times is:

$$\varphi(\alpha) = \binom{s}{\alpha} p^\alpha q^{s-\alpha},$$

which is also the probability of the existence of the frequency number  $\alpha$ . The variable in the binomial expansion is  $\alpha$ , which may assume all values from 0 to  $s$  inclusive.

We now first of all proceed to find the expected value—or the mathematical expectation—of the following quantities:

$$\alpha, [\alpha - e(\alpha)] \text{ and } [\alpha - e(\alpha)]^2.$$

We shall presently show the reason for the selection of the above expressions, which perhaps may appear at the present, somewhat puzzling to the student.

In mathematical symbols the expected values of the above quantities are expressed as follows:

$$e(\alpha) = \Sigma \alpha \varphi(\alpha), e[\alpha - e(\alpha)] = \Sigma [\alpha - e(\alpha)] \varphi(\alpha)$$

and

$$e[\alpha - e(\alpha)]^2 = \Sigma [\alpha - e(\alpha)]^2 \varphi(\alpha)$$

and the summation is to take place from  $\alpha = 0$  and to  $\alpha = s$ .

**65. Summation Method of Laplace. The Mean Error.**—The analytical difficulty lies in the summation of the expressions as given above. Laplace was the first to give a compact expression for the different sums in a simple and elegant manner. By the introduction of the parameter  $t$  Laplace writes:

$$\varphi(\alpha) = (p + q)^s = \sum \binom{s}{\alpha} p^\alpha q^{s-\alpha}$$

as

$$\varphi(t\alpha) = (tp + q)^s = \sum \binom{s}{\alpha} (tp)^\alpha q^{s-\alpha}.$$

Differentiating with respect to  $t$ , which it must be remembered is introduced as an auxiliary parameter only, we have:

$$\varphi'(t\alpha) = sp(tp + q)^{s-1} = \sum \alpha p \binom{s}{\alpha} (tp)^{\alpha-1} q^{s-\alpha}.$$

Letting  $t$  assume the special value 1 the above sum becomes  $e(\alpha)$  or

$$e(\alpha) = \sum \alpha \binom{s}{\alpha} p^\alpha q^{s-\alpha} = sp(p + q)^{s-1} = sp. \quad (I.)$$

We might, however, have obtained the same result in a much shorter manner by the following consideration. The expectation for a single event among the  $s$  events is equal to  $p$ . Since all the events are independent of each other, it follows from the addition theorem that the complete expectation of the total  $s$  cases is equal to  $sp$ .

We next proceed to determine the expression:  $e[\alpha - e(\alpha)]$  or the expected value of the differences between the constant,  $e(\alpha) = sp$  and the individual values 1, 2, 3,  $\dots$ ,  $s$  which  $\alpha$  may assume in the binomial expansion.

The difference  $\alpha - e(\alpha)$  is known as the departure or deviation from the expected value, some of these deviations will be positive, namely all the values situated to the right of the maximum term, which also is the most probable term in the expansion  $(p + q)^s$ , while the  $\alpha$ 's situated to the left of the maximum value of  $\alpha$  will be less in magnitude than the largest  $\alpha = sp$  and the deviation will therefore be negative. On account of the symmetrical form of the binomial expansion we may expect an

equal number of positive and negative deviations which, taken two and two at a time, are equal in absolute magnitude. The algebraic sum of all the deviations may therefore be expected to be equal to zero. We shall, however, in a rigidly analytical manner prove that this is actually so. We have

$$e[\alpha - e(\alpha)] = \Sigma[\alpha - e(\alpha)]\varphi(\alpha) = \Sigma\alpha\varphi(\alpha) - \Sigma e(\alpha)\varphi(\alpha) \\ = \Sigma\alpha\varphi(\alpha) - sp\Sigma\varphi(\alpha).$$

The first term in this last expression we found, however, to be equal to  $e(\alpha) = sp$ , and we have finally:

$$e[\alpha - e(\alpha)] = sp - sp = 0.$$

By squaring the quantity,  $\alpha - e(\alpha)$ , we get  $\alpha^2 - 2\alpha e(\alpha) + [e(\alpha)]^2$ , which is always positive no matter if the above difference is negative.

As a preliminary step we shall find

$$e(\alpha^2) = \Sigma\alpha^2\varphi(\alpha).$$

Introducing the auxiliary parameter,  $t$ , we get:

$$\Sigma \binom{s}{\alpha} (tp)^{\alpha} q^{s-\alpha} = (tp + q)^s.$$

The first derivative with respect to  $t$  is:

$$\Sigma p\alpha \binom{s}{\alpha} (tp)^{\alpha-1} q^{s-\alpha} = sp(tp + q)^{s-1}.$$

Multiplying both sides of the equation by  $tp$ , we have:

$$\Sigma p\alpha (tp)^{\alpha} q^{s-\alpha} \binom{s}{\alpha} = sp^2(tp + q)^{s-1}.$$

Differentiating we get:

$$\Sigma p^2\alpha^2 \binom{s}{\alpha} (tp)^{\alpha-1} q^{s-\alpha} = sp^2(tp + q)^{s-1} + s(s-1)p^2t(tp + q)^{s-2}.$$

Dividing through with the constant factor  $p$  and letting  $t = 1$  we have:

$$\Sigma\alpha^2 \binom{s}{\alpha} p^{\alpha} q^{s-\alpha} = s^2p^2 + sp(1-p) = s^2p^2 + spq.$$

The expression on the left side is, however, nothing less than the algebraic sum of  $\Sigma\alpha^2\varphi(\alpha)$  or simply  $e(\alpha^2)$ . This leaves the final result:

$$e(\alpha^2) = s^2 p^2 + spq.$$

We have now:

$$[\alpha - e(\alpha)]^2 = \alpha^2 - 2\alpha e(\alpha) + [e(\alpha)]^2,$$

from which it follows:

$$e[\alpha - e(\alpha)]^2 = s^2 p^2 + spq - 2s^2 p^2 + s^2 p^2 = spq.$$

Denoting this latter quantity by the symbol  $[\epsilon(\alpha)]^2$  we have:

$$[\epsilon(\alpha)]^2 = e[\alpha - e(\alpha)]^2 = spq, \text{ or } \epsilon(\alpha) = \sqrt{spq}. \quad (\text{II.})$$

The quantity  $\epsilon(\alpha)$  or simply  $\epsilon$  is commonly known as the mean error of the frequency number  $\alpha$  in the Bernoullian expansion. The mean error is one of the most useful functions in the theory of probabilities and furnishes one of the most powerful tools of the statistician.

**66. Mean Error of Various Algebraic Expressions.**—We next proceed to prove some general theorems connected with the mean error. The mean error of the sum of two observed variables,  $\alpha$  and  $\beta$ , is given by the formula:

$$\epsilon(\alpha + \beta) = \sqrt{\epsilon^2(\alpha) + \epsilon^2(\beta)}.$$

**Proof:** Let  $e(\alpha) = \Sigma \alpha \varphi(\alpha)$  and  $e(\beta) = \Sigma \beta \psi(\beta)$

$$\epsilon^2(\alpha) = \Sigma [\alpha - e(\alpha)]^2 \varphi(\alpha) \text{ and } \epsilon^2(\beta) = \Sigma [\beta - e(\beta)]^2 \psi(\beta)$$

be the respective expressions for the probable values and the mean errors of  $\alpha$  and  $\beta$  where of course  $\Sigma \varphi(\alpha) = 1$  and  $\Sigma \psi(\beta) = 1$ . Now  $\varphi(\alpha_r)$  is the probability for the occurrence of the special value  $\alpha_r$  of the variable values, in the same way  $\psi(\beta_\mu)$  is the probability for the occurrence of  $\beta_\mu$ . If  $\alpha$  and  $\beta$  are independent of each other, then according to the multiplication theorem,  $\varphi(\alpha_r)\psi(\beta_\mu)$  represents the probability for the simultaneous occurrence of  $\alpha_r$  and  $\beta_\mu$  as well as the probability of the occurrence of the difference:  $\alpha_r + \beta_\mu - e(\alpha) - e(\beta)$ , since the probable values  $e(\alpha)$  and  $e(\beta)$  are constant quantities independent of either  $\alpha$  or  $\beta$ .

If  $\epsilon$  denotes the mean error of  $\alpha + \beta$  then it follows from the definition of  $\epsilon$  that  $\epsilon^2 = \Sigma \Sigma [\alpha + \beta - e(\alpha) - e(\beta)]^2 \varphi(\alpha) \psi(\beta)$  where the double summation is to take place for all possible values of the variables  $\alpha$  and  $\beta$ .

The above expression may be written as:

$$\epsilon^2 = \Sigma \Sigma [\alpha - e(\alpha) + \beta - e(\beta)]^2 \varphi(\alpha) \psi(\beta),$$

or

$$\epsilon^2 = \Sigma \Sigma [\alpha - e(\alpha)]^2 \varphi(\alpha) \psi(\beta) + 2 \Sigma \Sigma [\alpha - e(\alpha)] [\beta - e(\beta)] \varphi(\alpha) \psi(\beta) + \Sigma \Sigma [\beta - e(\beta)]^2 \varphi(\alpha) \psi(\beta).$$

A mere inspection will satisfy that the first and the last terms of this expression equals  $\epsilon^2(\alpha)$  and  $\epsilon^2(\beta)$  respectively. The first term may be written as follows:

$$\Sigma [\alpha - e(\alpha)]^2 \varphi(\alpha) \Sigma \psi(\beta) = \epsilon^2(\alpha)$$

since  $\Sigma \psi(\beta) = 1$ . The same also holds true for the last term. With regard to the middle term we found before that

$$e[\alpha - e(\alpha)] = 0.$$

Hence it follows by mere inspection that this term becomes 0. Thus we finally have:

$$\epsilon^2(\alpha + \beta) = \epsilon^2(\alpha) + \epsilon^2(\beta) \text{ or } \epsilon(\alpha + \beta) = \sqrt{\epsilon^2(\alpha) + \epsilon^2(\beta)}.$$

Since the middle term is always 0, it follows a fortiori

$$\epsilon(\alpha - \beta) = \sqrt{\epsilon^2(\alpha) + \epsilon^2(\beta)},$$

also that

$$\epsilon(k\alpha) = k\epsilon(\alpha),$$

where  $k$  is a constant. This gives us the following theorems: The mean error of the sum or of the difference of two quantities is equal to the square root of the sum of the squares of each separate mean error. The mean error of any quantity multiplied by a constant is equal to this same constant multiplied by the mean error of the quantity. (See Appendix.)

The above theorems may easily be extended to any number of variables:  $\alpha, \beta, \gamma \dots$  so that in general we have

$$\epsilon(\alpha + \beta + \gamma \dots) = \sqrt{\epsilon^2(\alpha) + \epsilon^2(\beta) + \epsilon^2(\gamma) + \dots}.$$

We shall later make use of this formula by a comparison of the different rates of mortality among different population groups.

So far we have computed the mean error for the absolute frequencies of  $\alpha$ , and the quantity  $\sqrt{spq}$  was compared with the most probable number of successes  $sp$ . But it may also be useful to know the mean error of the relative frequencies. This calculation is performed by reducing the mean error of the absolute

frequencies to the same degree as these absolute frequencies are reduced to relative frequencies. We saw before that  $e(\alpha) = sp$ . The relative frequency of the probable value is  $e(\alpha)/s = sp/s = p$ . The mean error of  $p$  therefore is

$$\epsilon[e(\alpha):s] = \sqrt{\frac{pq}{s}}.$$

The following remarks of Westergaard are worthy of note: "When a length is measured in meters and this measure may be effected with an uncertainty of say 2 meters, the length in centimetres is then simply found by multiplication by 100 and the uncertainty is 200 cm. When we wish to find the mean error of  $p$  instead of  $sp$  we only need to divide the mean error  $\sqrt{spq}$  by  $s$ , which gives  $\sqrt{pq/s}$ ."

The same result is also easily obtained from the formula

$$\epsilon(k\alpha) = k\epsilon(\alpha)$$

when we let  $k = 1/s$ .

**67. Tchebycheff's Theorem.**—Tchebycheff's brochure appeared first in Liouville's Journal for 1866 under the title "Des valeurs Moyennes." A later demonstration was given by the Italian mathematician, Pizetti, in the annals of the University of Geneva for 1892. The nucleus in both Tchebycheff's and Pizetti's investigations is the expression for the mean error:

$$\epsilon(\xi) = \Sigma[\xi - e(\xi)]^2\varphi(\xi). \quad (1)$$

The variable  $\xi$  may be of any form whatsoever, it may thus for instance be the sum of several variables:  $\alpha, \beta, \gamma \dots$  while  $\varphi(\xi)$  is the ordinary probability function for the occurrence of  $\xi$ . Let us denote the difference:  $\xi_r - e(\xi_r)$  by  $v_r$  ( $r = 1, 2, 3 \dots s$ ). We may then write the above expression for  $\epsilon(\xi)$  as:

$$\varphi(\xi_1) \frac{v_1^2}{a^2} + \varphi(\xi_2) \frac{v_2^2}{a^2} + \varphi(\xi_3) \frac{v_3^2}{a^2} + \dots \varphi(\xi_s) \frac{v_s^2}{a^2} = \frac{\epsilon^2(\xi)}{a^2} \quad (2)$$

where  $a$  is an arbitrarily chosen constant, but always larger than  $\epsilon(\xi)$  in absolute magnitude. If we, in the above equation, select all the  $v$ 's which are larger than  $a$  in absolute magnitude together with their corresponding probabilities,  $\varphi(\xi)$  and denote all

such quantities by  $v'$ ,  $v''$ ,  $v'''$ , ... and  $\varphi(\xi)'$ ,  $\varphi(\xi)''$ ,  $\varphi(\xi)'''$ , ... respectively, we have evidently:

$$\frac{\varphi(\xi)'v'^2}{a^2} + \frac{\varphi(\xi)''v''^2}{a^2} + \frac{\varphi(\xi)'''v'''^2}{a^2} + \dots < \frac{\epsilon^2(\xi)}{a^2} \quad (3)$$

For any one of these different  $v$ 's which is larger in absolute magnitude than  $a$

$$\frac{v^2}{a^2} > 1$$

from which it follows a fortiori:

$$\varphi(\xi)' + \varphi(\xi)'' + \dots = \Sigma \varphi'(\xi) < \frac{\epsilon^2(\xi)}{a^2}. \quad (3a)$$

In this latter inequality,  $\Sigma \varphi'(\xi)$  is the total probability for the occurrence of a deviation from  $e(\xi)$  larger than  $a$  in absolute magnitude.

Let now  $P_T$  be the probability that the absolute value of the mean error is *not* larger than  $a$ ; then  $1 - P_T$  is the total probability that the mean error is larger than  $a$ . We have thus from the inequality (3a)

$$1 - P_T < \frac{\epsilon^2(\xi)}{a^2} \quad \text{or} \quad P_T > 1 - \frac{\epsilon^2(\xi)}{a^2}. \quad (4)$$

Let also  $a = \lambda \epsilon(\xi)$ . We then have by a mere substitution in the above inequality:

$$P_T > 1 - \frac{1}{\lambda^2}. \quad (5)$$

This constitutes the first of Tchebycheff's criterions which says:

*The probability that the absolute value of the difference  $|\alpha - e(\alpha)|$  does not exceed the mean error by a certain multiple,  $\lambda$ , ( $\lambda > 1$ ) is greater than  $1 - (1/\lambda^2)$ .*

Now we made no restrictions as to the variable,  $\xi$ , which may be composed of the sum of several independent variables,  $\alpha$ ,  $\beta$ ,  $\gamma$ , ... We saw before that

$$\epsilon^2(\alpha + \beta + \gamma + \dots) = \epsilon^2(\alpha) + \epsilon^2(\beta) + \epsilon^2(\gamma) + \dots$$

Tchebycheff's criterion may therefore be extended as follows:

*The Tchebycheffian probability,  $P_T$ , that the difference  $|\alpha + \beta + \gamma + \dots - e(\alpha) - e(\beta) - e(\gamma) - \dots|$  will never exceed the mean error  $\epsilon$  by a certain multiple,  $\lambda > 1$ , is greater than  $1 - (1/\lambda^2)$ .*

**68. The Theorems of Poisson and Bernoulli proved by the application of the Tchebycheffian Criterion.**—Bernoulli in his researches limited himself to the solution of the problem in which the probabilities for the observed event remained constant during the total number of observations or trials. Poisson has treated the more general case, wherein the individual probability for the happening of the event in a single trial varies during the total  $s$  trials. This may probably best be illustrated by an urn schema. Suppose we have  $s$  urns  $U_1, U_2, \dots U_s$  with white and black balls in various numbers. Let the probability for drawing a white ball from the urns  $U_1, U_2, \dots U_s$  in a single trial be  $p_1, p_2, \dots p_s$  respectively,  $q_1, q_2, \dots q_s$  the chances for drawing a black ball in a single trial. If a ball is drawn from each urn, what is the probability of a drawing  $\alpha$  white and  $s - \alpha$  black balls in  $s$  trials? It is easily seen that the Bernoullian Theorem is a special case when the contents of the  $s$  urns and the respective probabilities for drawing a white ball in a single trial are the same for all urns.

**69. Bernoullian Scheme.**—We shall now show how the Tchebycheffian criterions may be used in answering the question given above. First of all we shall start with the simpler case of the Bernoullian urn-schema. Here the probability for drawing a white or a black ball from each of the  $s$  urns in a single trial is  $p$  and  $q$  respectively. The square of the mean error in a single trial is  $pq$ . From the formulas in § 66 it then follows:

$$\epsilon^2 = \epsilon_1^2 + \epsilon_2^2 + \dots = pq + pq + pq + \dots s \text{ times} = spq$$

or

$$\epsilon = \sqrt{spq}.$$

While the above expression gives us the mean error of the absolute frequency of the variable  $\alpha$ , the relative frequency of  $\alpha$  to the total number of trials,  $s$ , is given as

$$\epsilon = \frac{\sqrt{pq}}{\sqrt{s}}.$$

We now ask: What is the total probability that the absolute deviation of the relative frequency  $\alpha/s$  from its expected value  $sp/s = p$  never becomes larger than  $\lambda$  times the mean error,

$\epsilon = \sqrt{pq/s}$ ? Letting  $\lambda = \sqrt{s}/t$  and using the symbols  $P_T$  for this particular probability, we have according to Tchebycheff's criterion:

$$P_T > 1 - 1/\lambda^2, \text{ or } P_T > 1 - t^2/s.$$

Since the mean error is equal to  $\sqrt{pq/s}$  we have:

$$\lambda\epsilon = \frac{\sqrt{pq}}{t}.$$

The answer to our question above follows now a fortiori as follows:

The total probability that the absolute deviation of the relative frequency from the postulated a priori probability,  $p$ , never exceeds the quantity,  $\sqrt{pq}/t$ , is greater than  $1 - (t^2/s)$ .

By taking  $t$  large enough we may reduce  $\sqrt{pq}/t$  (where  $pq$  is a fraction whose maximum value never can exceed  $1 \div 4$ ), below any previously assigned quantity,  $\delta$ , however small. If, for instance, we choose the value .0001 for  $\delta$ , we may rest assured that  $\sqrt{pq}/t$  will be less than  $\delta$  when we take  $t$  larger than 5000. But no matter how large  $t$  is, so long as it remains a finite number, by letting  $s = \infty$  as a limiting value,  $t^2/s$  will simultaneously approach 0 as a limiting value. From the deductions thus derived we are now able to draw the following conclusions:

1) By letting  $s = \infty$  as a limiting value, the probability,  $P_T$ , that the absolute difference between the relative frequency  $\alpha/s$  and the postulated a priori probability,  $p$ , never becomes greater than  $\sqrt{pq}/t$  approaches 1 or certainty as a limit.

2) By choosing the quantity,  $t$ , which is less than  $\lim_{s=\infty} \sqrt{s}$ , sufficiently great, we may bring  $\sqrt{pq}/t$  below any previously assigned quantity,  $\delta$ , or make the difference between  $p$  and  $\alpha/s$  as small as we please.

From these conclusions we obtain a fortiori the following

$$\lim_{s=\infty} \frac{\alpha}{s} = p.$$

This constitutes the essential features of the Bernoullian Theorem.

70. Poisson's Scheme.—Let  $p_1$  denote the postulated probability for success in the first trial,  $p_2$  in the second,  $p_3$  in the

third, etc., and let furthermore  $q_1, q_2, q_3, \dots$  be the respective probabilities for the corresponding failures. If the trial (observation) is repeated  $s$  times we obtain the following values for the probable or expected value of the frequency for successes  $e(\alpha)$  and the mean error  $\epsilon$

$$e(\alpha) = p_1 + p_2 + p_3 + \dots p_s = \Sigma p_i,$$

$$\epsilon = \sqrt{p_1 q_1 + p_2 q_2 + p_3 q_3 + \dots p_s q_s} = \sqrt{\Sigma p_i q_i} \quad (i = 1, 2, 3, \dots s)$$

If by  $p_0$  and  $q_0$  we denote the arithmetic mean or the average value of the  $s$   $p$ 's and  $s$   $q$ 's, such that

$$p_0 = \frac{p_1 + p_2 + p_3 + \dots p_s}{s} \quad (3)$$

$$q_0 = \frac{q_1 + q_2 + q_3 + \dots q_s}{s} \quad (4)$$

and assume that  $p_0$  and  $q_0$  denote the constant probabilities during each of the  $s$  trials (observations), we should according to the Bernoullian Theorem have:

$$e(\alpha_B) = s p_0 \quad (5)$$

$$\epsilon(\alpha_B) = \sqrt{s p_0 q_0} \quad (6)$$

where  $\alpha_B$  stands for the absolute frequency in a Bernoullian series.

An actual comparison of (1) and (5) and (3) shows that:

$$e(\alpha_P) = e(\alpha_B) \quad (7)$$

where  $\alpha_P$  is the symbol for the absolute frequency in a Poisson series. In other words: If the  $s$  trials had been performed with constant probability for success equal to  $p_0$  instead of with varying probabilities  $p_1, p_2, \dots p_s$ , the expected or probable value would be the same for the Bernoullian and Poisson scheme.

With regard to the mean error we find, however, after a little calculation,

$$\epsilon_P^2(\alpha) = \epsilon_B^2(\alpha) - \Sigma (p_i - p_0)^2. \quad (8)$$

The expression for the mean error in Poisson's Theorem is of the following form

$$\epsilon_P = \sqrt{p_1 q_1 + p_2 q_2 + p_3 q_3 + \dots p_i q_i} = \sqrt{\Sigma p_i q_i} \quad (i = 1, 2, 3 \dots s).$$

Now  $p_i q_i$  may be transformed as follows:

Writing

$$p_i = p_0 + (p_i - p_0)$$

$$q_i = q_0 - (p_i - p_0)$$

and multiplying we obtain:

$$p_i q_i = p_0 q_0 - (p_i - p_0)(p_0 - q_0) - (p_i - p_0)^2,$$

and summing up for all values of  $i$  from  $i = 1$  to  $i = s$  we have:

$$\epsilon_P^2 = s p_0 q_0 - \Sigma (p_i - p_0)^2 = \epsilon_B^2 - \Sigma (p_i - p_0)^2.$$

As  $(p_i - p_0)^2$  always is a positive quantity, it is readily seen that the mean error in a Poisson scheme is always less than the mean error in the corresponding Bernoullian series.

Writing  $\epsilon$  as follows:

$$\begin{aligned} \epsilon &= \sqrt{p_1 q_1 + p_2 q_2 + \cdots + p_s q_s} \\ &= \sqrt{s} \sqrt{\frac{p_1 + \cdots + p_s}{s} - \frac{p_1^2 + \cdots + p_s^2}{s}} \end{aligned}$$

and letting  $\lambda = \sqrt{s}/t$ , we have according to Tchebycheff's Theorem the following rule: The probability  $P_T$  that the relative frequency remains inside the limits:

$$\begin{aligned} \frac{p_1 + p_2 + \cdots + p_s}{s} \pm \frac{\sqrt{s}}{t} \epsilon \left( \frac{\alpha}{s} \right) &= \frac{p_1 + p_2 + \cdots + p_s}{s} \\ &\pm \frac{1}{t} \sqrt{\frac{p_1 + p_2 + \cdots + p_s}{s} - \frac{p_1^2 + p_2^2 + \cdots + p_s^2}{s}} \end{aligned}$$

is greater than  $1 - (1/\lambda^2)$  or  $1 - (t^2/s)$ .

By taking  $t$  sufficiently large and by letting  $s$  approach infinity as a limiting value the last term in the above difference, namely the average probability,  $p_0$ , and  $\lambda$  times the mean error, becomes smaller than any previously assigned quantity,  $\delta$ , however small, while  $P_T$  at the same time will approach 1 as a limit.

From this it now follows:

*When an infinite number of trials is made on an event, following the scheme of Poisson, then the expression:*

$$\lim_{s \rightarrow \infty} \frac{\alpha}{s} = \frac{p_1 + p_2 + \cdots + p_s}{s} = p_0.$$

The essential part of Poisson's Theorem is contained in this equation. When  $p = p_1 = p_2 = \dots p_s$  we have a Bernoullian series and obtain:

$$\lim_{s=\infty} \frac{\alpha}{s} = p,$$

which result we already derived above in a direct way.

**71. Relation between Empirical Frequency Ratios and Mathematical Probabilities.**—In the above limit,  $\alpha$  indicates the total number of lucky events while  $s$  is the total number of trials, the quotient  $\alpha \div s$  then is nothing more than the empirical probability as defined in the preceding paragraphs. Both the Bernoullian and Poisson Theorems show that this empirical probability approaches the postulated a priori probability,  $p$ , (or the average probability  $p_0$ ) as a limiting value.

In this way we have succeeded in extending the theory of probability to other problems than the conventional kind involved in the games of chance or drawings of balls from urns. We do not need to limit our investigations to problems where we are able to determine a priori the probability for the happening of an event in a single trial, but limit ourselves to postulate the existence of such an a priori probability.

A large number of trials or observations is made on a certain event  $E$ . This event is now observed to have occurred  $\alpha$  times during the  $s$  total trials. To illustrate: An urn contains red and white balls, the total number of balls being unknown, a single ball is drawn and its color noted. This ball is replaced and the contents of the urn is mixed. A second drawing is made and the color of the drawn ball noted before the ball is put back in the urn. Let this process be repeated  $s$  times, where  $s$  is a large number, and furthermore let  $\alpha$  be the number of red balls which appeared during the  $s$  trials.

The quotient  $\alpha \div s$  we now call the empirical or a posteriori probability for the observed event, in this particular case the a posteriori probability for the drawing of a red ball. When  $s = \infty$  the Bernoullian Theorem tells us that the empirical probability found in this manner and the postulated a priori probability whose numerical value, however, was unknown before the drawings took place, are identical as far as numerical

magnitude is concerned. As we already observed in the introductory remarks to this chapter it is impossible to perform a certain experiment an infinite number of times, and it is therefore out of the question to determine the limiting and ideal value of the posteriori probability, and we must satisfy ourselves with an approximation by performing a finite number of trials, or let  $s$  be a finite number. The quotient  $\alpha \div s$  is then the empirical approximate a posteriori probability. We know also that although this quotient is an approximation of the postulated a priori probability only, that by increasing  $s$  or what amounts to the same thing, by making a large number of trials, the difference between the approximate empirical probability ratio,  $\alpha \div s$ , and the a priori probability,  $p$ , becomes smaller as the number of trials is increased. But how small is the difference? Or how many times shall we repeat the trials (observations) so that, for practical purposes, we may disregard this difference? It does not suffice to be satisfied with the fact that the difference becomes proportionately smaller the greater we make the number of trials and merely insist that in order to avoid large errors it is only necessary to operate with very large numbers. Immediately the question arises: What constitutes a large number? Is 100 a large number, or is 1,000, 10,000, 100,000 or even a million an answer to this question? As long as this question remains unanswered, it helps but little to poke upon the "law of large numbers," a tendency which unfortunately is too manifest in many statistical researches by amateur statisticians. As long as a definition, much less than a numerical determination of the range of "small numbers" is lacking, little stress ought to be laid on such remarks based in the metaphorical terms of "small" and "large" numbers.

**72. Application of the Tchebycheffian Criterion.**—It is readily seen that even a rough quantitative determination of the difference between the approximate a posteriori probability and the postulated a priori probability based upon the mere vague statement of "large numbers" is utterly impossible, and it remains to be seen, therefore, if the theory of probability offers us a criterion that might serve as a preliminary test for the above difference. To restate our problem: *If  $p$  is the postulated a priori*

probability and  $\alpha \div s$  is the empirical probability (a posteriori) or relative frequency of the event,  $E$ , what is the probability that the difference,  $|(\alpha/s) - p|$  does not exceed a previously assigned quantity? In the mean error and the associated theorem of Tchebycheff we have a simple and easily applied criterion to test this probability.

Tchebycheff's rule states that the probability,  $P_r$ , of a deviation of a variable from its probable value, not larger than  $\lambda$  times its mean error, is greater than  $1 - (1/\lambda^2)$ .

For

$$\lambda = 3 \quad P_r > 1 - \frac{1}{9} = 0.888$$

$$\lambda = 4 \quad P_r > 1 - \frac{1}{16} = 0.937$$

$$\lambda = 5 \quad P_r > 1 - \frac{1}{25} = 0.96.$$

This shows that a deviation from the expected or probable value of the variable equal to 4 or 5 times the mean error possesses a very small probability and such deviations are extremely rare.

Let us for example assume that the observed rate of mortality in a certain population group is equal to .0200. Let furthermore the number exposed to risk equal 10,000. The mean error is

then  $\left(\frac{.02 \times .98}{10,000}\right)^{\frac{1}{2}} = .0014$ . If the number of lives exposed to risk

was one million instead of 10,000, the mean error would be

$\left(\frac{.02 \times .98}{1,000,000}\right)^{\frac{1}{2}} = .00014$ . A deviation four times this latter quantity

is equal to .00056, and according to Tchebycheff's criterion the probability for the *non-occurrence* of a deviation above .00056 is greater than .937, or the probability of dying inside a year will not be higher than .0206 or less than .0194. For an observation series of 4,000,000 homogeneous elements we might by a similar procedure expect to find a rate of mortality between  $0.02 + 0.00028$  or  $0.02 - 0.00028$ . Thus we notice that the mean error of the relative frequency numbers decreases as the number of observations increases.

## CHAPTER X.

### THE THEORY OF DISPERSION AND THE CRITERIA OF LEXIS AND CHARLIER.

**73. Bernoullian, Poisson and Lexis Series.**—In the previous chapter we limited our discussion to single sets consisting of  $s$  individual trials and found in the mean error and the criterion of Tchebycheff a measure for the uncertainty with which the relative frequency ratio  $\alpha/s$  as well as the absolute frequency  $\alpha$  were affected. How will matters now turn out if, instead of a single set, we make  $N$  sets of trials? As already mentioned in paragraph 54, in general in  $N$  such sets we shall obtain  $N$  different values of  $\alpha$ , denoting the absolute frequency of the event represented by the sequence

$$\alpha_1, \alpha_2, \alpha_3, \dots \alpha_N.$$

Our object is now to investigate whether the distribution of the above values of  $\alpha$  around a certain norm is subject to some simple mathematical law and if possible to find a measure for such distributions.

In this connection it is of great importance whether the postulated a priori probabilities remain constant or not during the  $N$  sample sets. Three cases are of special importance to us.<sup>1</sup>

1. The probability of the happening of the event remains constant during all the  $N$  sets. The series as given by the absolute frequencies in each set is known as a *Bernoullian Series*.

2. The same probability varies from trial to trial inside each of  $N$  sample sets, the variations being the same from set to set. The series as given by the absolute frequencies is in this case known as a *Poisson Series*.

3. The probability remains constant in any one particular set but varies from set to set. The absolute frequency series as produced in this way is called a *Lexis Series*.

The above definition of these three series may, perhaps, be made clearer by a concrete urn scheme.

<sup>1</sup> The terminology is due to Charlier.

*A. Bernoullian Series.*— $s$  balls are drawn one at a time from an urn, containing black and white balls in *constant proportion* during all drawings. Such drawings constitute a sample set. Let us in this particular set have obtained say  $\alpha_1$  white and  $\beta_1$  black balls, where  $\alpha_1 + \beta_1 = s$ . We make  $N$  sets of drawings under the same conditions, keeping a record of white balls drawn in each set. The number sequence thus obtained,

$$\alpha_1, \alpha_2, \alpha_3, \dots \alpha_N.$$

is a Bernoullian Series.

*B. Poisson Series.*— $s$  individual urns contain white and black balls, the proportion of white to black varying from urn to urn. A single ball is drawn from each urn and its color noted. In this way we get  $\alpha_1$  white and  $\beta_1$  black balls constituting a set. The balls thus drawn are replaced in their respective urns and a second set of  $s$  drawings is performed as before, resulting in  $\alpha_2$  white and  $\beta_2$  black balls. The number sequence,

$$\alpha_1, \alpha_2, \alpha_3, \dots \alpha_N,$$

of white balls in  $N$  sets represents a Poisson Series.

*C. Lexis Series.*— $s$  balls are drawn one at a time under the same conditions as set No. 1 in the Bernoullian series. The  $\alpha_1$  white and  $\beta_1$  black thus drawn constitute the first set. In the second and following set the composition of the urn is changed from set to set. The number sequence representing the number of white balls in the  $N$  respective sets:

$$\alpha_1, \alpha_2, \alpha_3, \dots \alpha_N$$

is a Lexian Series. The scheme of drawings is the same as in the Bernoullian Series except that the proportion of white to black balls varies from set to set.

**74. The Mean and Dispersion.**—Since we have no a priori reasons for choosing any one particular value of the various  $\alpha$ 's of the above sequences in preference to any other, we might give equal weight to each set and take the arithmetic mean as defined by the formula:

$$M = \frac{\alpha_1 + \alpha_2 + \alpha_3 + \dots \alpha_N}{N} \quad (I)$$

of the  $N$  values of  $\alpha$ .

It will be unnecessary to enter into a detailed discussion of the mean, which is a quantity used on numerous occasions in every day life. We shall, however, define another important function known as the *dispersion* (standard deviation). The dispersion is denoted by the Greek letter,  $\sigma$ , and is defined by the formula

$$\sigma^2 = \frac{(\alpha_1 - M)^2 + (\alpha_2 - M)^2 + \dots (\alpha_N - M)^2}{N}. \quad (\text{II})$$

We shall now attempt to find the expected value of the mean and the dispersion in the three series. First of all take the Bernoullian Series. Let the constant probability for success in a single trial be  $p_0$ . We have then for the various expected values or mathematical expectations of  $\alpha$ :

$$\text{Set No. 1:} \quad e(\alpha_1) = sp_0$$

$$\text{Set No. 2:} \quad e(\alpha_2) = sp_0$$

$$\cdot \quad \cdot \quad \cdot$$

$$\text{Set No. } N: \quad e(\alpha_N) = sp_0$$

or:

$$\frac{e(\alpha_1) + e(\alpha_2) + \dots + e(\alpha_N)}{N} = \frac{\Sigma e(\alpha_r)}{N} = \frac{Nsp_0}{N} = sp_0,$$

which shows that the mean in a Bernoullian Series of  $N$  sample sets is equal to the expected value of the absolute frequency in a single set.

In regard to the dispersion we have for the various sets:

$$\text{Set No. 1:} \quad e(\alpha_1 - M)^2 = e^2(\alpha_1) = sp_0q_0$$

$$\text{Set No. 2:} \quad e(\alpha_2 - M)^2 = e^2(\alpha_2) = sp_0q_0$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\text{Set No. } N: \quad e(\alpha_N - M)^2 = e^2(\alpha_N) = sp_0q_0$$

Summing up and forming the mean we obtain for the expected value of the dispersion in a Bernoullian Series, which we shall denote by the symbol  $\sigma_B$ :

$$\sigma_B^2 = \frac{\Sigma e^2(\alpha_r)}{N} = \frac{Nsp_0q_0}{N} = sp_0q_0.$$

This result shows that the dispersion in a Bernoullian Series is equal to the mean error,  $\epsilon$ , in a single set.

We now proceed to the Poisson Series. Let  $p_1$  be the mathematical probability of the happening of the event in the first trial,  $p_2$  be the probability in the second trial and so on for all trials, and let us furthermore denote the means of the  $p$ 's and  $q$ 's by:

$$p_0 = \frac{p_1 + p_2 + p_3 \cdots + p_s}{s}$$

$$q_0 = \frac{q_1 + q_2 + q_3 \cdots + q_s}{s}$$

Applying a similar analysis as above we have:

$$\text{Set No. 1: } e(\alpha_1) = p_1 + p_2 + \cdots + p_s = sp_0$$

$$\text{Set No. 2: } e(\alpha_2) = p_1 + p_2 + \cdots + p_s = sp_0$$

$$\vdots$$

$$\text{Set No. } N: e(\alpha_N) = p_1 + p_2 + \cdots + p_s = sp_0$$

The actual summation of the above values of  $e(\alpha)$  gives us the following value of the mean in a Poisson Series:

$$M_P = sp_0.$$

Let us for a moment assume that all the drawings had been performed with a constant probability,  $p_0$ . According to the Bernoullian scheme we should then have:

$$M_B = sp_0.$$

An actual comparison shows that  $M_B = M_P$ . This shows that the same mean result is obtained if we draw  $s$  balls from the urns  $U_1, U_2, \cdots U_s$  with their corresponding probabilities  $p_1, p_2, \cdots p_s$  for drawing a white ball, as would be obtained if we drew all the  $s$  balls from a single urn where the composition is such that the ratio of the number of white to that of black balls is as  $p_0 : q_0$ , where  $p_0$  and  $q_0$  are defined as above.

Let us now see how matters turn out in regard to the dispersion. We have for the  $N$  sets:

$$\text{Set No. 1: } e(\alpha_1 - M)^2 = p_1q_1 + p_2q_2 + \cdots = \Sigma p_i q_i = \epsilon^2(\alpha_1)$$

$$\text{Set No. 2: } e(\alpha_2 - M)^2 = p_1q_1 + p_2q_2 + \cdots = \Sigma p_i q_i = \epsilon^2(\alpha_2)$$

$$\vdots$$

$$\text{Set No. } N: e(\alpha_N - M)^2 = p_1q_1 + p_2q_2 + \cdots = \Sigma p_i q_i = \epsilon^2(\alpha_N)$$

In § 70 we showed, however, that  $\Sigma p_r q_r$  could be expressed as follows:

$$\epsilon_P^2(\alpha) = sp_0 q_0 - \Sigma(p_r - p_0)^2 = \epsilon_B^2(\alpha) - \Sigma(p_r - p_0)^2.$$

A simple straightforward calculation gives us now for the dispersion,  $\sigma_P^2$ ,

$$\sigma_P^2 = \sigma_B^2 - \Sigma(p_r - p_0)^2.$$

In the corresponding Bernoullian Series with constant probability,  $p_0$ , the dispersion is equal to  $sp_0 q_0$ , which shows that the dispersion in a Poisson Series is less than the corresponding dispersion of the Bernoullian Series.

We finally come to the mean and the dispersion in the Lexian Series which we shall denote by  $M_L$  and  $\sigma_L$  respectively. Let us furthermore define the two quantities  $p_0$  and  $q_0$  as follows:

$$p_0 = \frac{p_1 + p_2 + \cdots + p_N}{N},$$

$$q_0 = \frac{q_1 + q_2 + \cdots + q_N}{N}.$$

A computation along similar lines as above gives us first for the mean,  $M_L$ :

$$\text{Set No. 1:} \quad e(\alpha_1) = sp_1$$

$$\text{Set No. 2:} \quad e(\alpha_2) = sp_2$$

$$\cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot$$

$$\text{Set No. } N: \quad e(\alpha_N) = sp_N$$

Thus we have:

$$M_L = \frac{\Sigma e(\alpha_r)}{N} = \frac{\Sigma sp_r}{N} = \frac{s[p_1 + p_2 + \cdots + p_N]}{N} = sp_0.$$

For the dispersion we have the following expectations:

$$\text{Set No. 1:} \quad e(sp_0 - \alpha_1)^2$$

$$\text{Set No. 2:} \quad e(sp_0 - \alpha_2)^2$$

$$\cdot \quad \cdot \quad \cdot$$

$$\cdot \quad \cdot \quad \cdot$$

$$\text{Set No. } N: \quad e(sp_0 - \alpha_N)^2$$

The expected value in the  $r$ th set is

$$e(sp_0 - \alpha_r)^2 = \Sigma(sp_0 - \alpha_r)^2 \varphi_r(\alpha),$$

where  $\varphi_\nu(\alpha)$  is the general term in the probability binomial:  $(p_\nu + q_\nu)^s = 1$ . An analysis along similar lines as in § 65 gives us now:

$$\begin{aligned} e(sp_0 - \alpha_\nu)^2 &= s^2 p_0^2 - 2s^2 p_0 p_\nu + s^2 p_\nu^2 + sp_\nu q_\nu \\ &= sp_\nu q_\nu + s^2(p_\nu - p_0)^2 \end{aligned}$$

as the expected value of the square of the difference between the mean and the absolute frequency in the  $\nu$ th set. For all  $N$  sets we then have

$$\sigma_L^2 = \frac{\sum sp_\nu q_\nu}{N} + \frac{s^2}{N} \sum (p_\nu - p_0)^2.$$

We have, however, the following identity:

$$\sum sp_\nu q_\nu = Np_0 q_0 - \sum (p_\nu - p_0)^2,$$

and hence

$$\sigma_L^2 = \sigma_B^2 + \frac{s^2 - s}{N} \sum (p_\nu - p_0)^2.$$

**74a. Mean or Average Deviation.**—Of quite another character than the standard deviation or dispersion is the so-called mean or average deviation,  $\vartheta$ , defined by means of the following relation:

$$\vartheta = \frac{|\alpha_1 - M| + |\alpha_2 - M| + |\alpha_3 - M| + \cdots + |\alpha_N - M|}{N},$$

where  $|\alpha_\nu - M|$  means the absolute difference between  $m$ , and  $M$ . We shall now proceed to determine the expected value of  $\vartheta$  on the assumption that the observed data follow the Bernoullian Law. The mean in a Bernoullian series with constant probability  $p_0$  we found before to be equal to  $sp_0$  which was the expected value of  $\alpha$  in a single sample set of  $s$  trials. The expected value of the absolute difference in the  $\nu$ th set is therefore:

$$e|\alpha_\nu - sp_0| = \sum |\alpha_\nu - sp_0| \varphi_\nu(\alpha),$$

where as usual  $\varphi_\nu(\alpha)$  is the binomial probability function.

The deviations from  $sp_0$  are partly positive and partly negative. We proved, however, before that

$$e(\alpha_\nu - sp_0) = \sum (\alpha_\nu - sp_0) \varphi_\nu(\alpha) = 0.$$

Hence it is readily seen that the algebraic sum of the positive deviations cancel the algebraic sum of the corresponding negative deviations so that  $e | \alpha - sp_0 |$  equals twice the sum of the positive deviations. Positive deviations occur for values of  $\alpha$  greater than  $sp_0$ , i. e., for all values which  $\alpha$  may assume from  $s$  to  $sp_0$  in the binomial expansion:  $(p_0 + q_0)^s$ .<sup>1</sup> Hence we have (omitting subscripts):

$$\begin{aligned} e | \alpha - sp | &= 2 \sum_{\alpha=s}^p (\alpha - sp) \binom{s}{\alpha} p^\alpha q^{s-\alpha} \\ &= 2 \left\{ \sum_{\alpha=s}^p \alpha \binom{s}{\alpha} p^\alpha q^{s-\alpha} - sp \sum_{\alpha=s}^p \binom{s}{\alpha} p^\alpha q^{s-\alpha} \right\}. \end{aligned}$$

The second of these sums represents the following function of  $p$  and  $q$

$$f(p, q) = p^s + \binom{s}{1} p^{s-1} q + \binom{s}{2} p^{s-2} q^2 + \dots + \binom{s}{sq} p^{sq} q^{s-q}.$$

By partial differentiation in respect to  $p$  and by following multiplication by  $p$  we have:

$$\begin{aligned} p \frac{\partial f}{\partial p} &= sp^s + (s-1) \binom{s}{1} p^{s-1} q + (s-2) \binom{s}{2} p^{s-2} q^2 + \dots \\ &\quad + sp \binom{s}{sq} p^{sq} q^{s-q} \\ &= \sum_{\alpha=s}^p \alpha \binom{s}{\alpha} p^\alpha q^{s-\alpha}. \end{aligned}$$

Hence we may write:

$$e | \alpha - sp | = 2 \left\{ p \frac{\partial f}{\partial p} - spf \right\}.$$

Furthermore  $f(p, q)$  is a homogenous function in respect to  $p$  and  $q$  of the  $s$ th order. We may then apply the following well known Eulerian Theorem from the differential calculus: If  $f(p, q)$  is homogenous and has continuous first partial derivatives then

$$sf = p \frac{\partial f}{\partial p} + q \frac{\partial f}{\partial q}.$$

Using this relation we may write:

$$e | \alpha - sp | = 2 \left\{ p \frac{\partial f}{\partial p} - spf \right\} = 2pq \left\{ \frac{\partial f}{\partial p} - \frac{\partial f}{\partial q} \right\}.$$

<sup>1</sup>  $Sp_0$  is taken to the nearest integer.

The partial derivatives of  $f(p, q)$  with respect to  $p$  and  $q$  are of the form:

$$\begin{aligned}\frac{\partial f}{\partial p} &= sp^{s-1} + s(s-1)p^{s-2} + \dots + \frac{s(s-1) \dots (sp+1)}{1 \cdot 2 \cdot 3 \dots (sq-1)} p^{sp} q^{sq-1} \\ &\quad + \frac{s(s-1) \dots sp}{1 \cdot 2 \cdot 3 \dots sq} p^{sp-1} q^{sq} \\ \frac{\partial f}{\partial q} &= sp^{s-1} + s(s-1)p^{s-2} + \dots + \frac{s(s-1) \dots (sp+1)}{1 \cdot 2 \cdot 3 \dots (sq-1)} p^{sp} q^{sq-1}\end{aligned}$$

Hence we have:

$$\frac{\partial f}{\partial q} - \frac{\partial f}{\partial p} = \frac{s(s-1) \dots sp}{1 \cdot 2 \cdot 3 \dots sq} p^{sp-1} q^{sq} = s \left\{ \frac{s}{sp! sq!} p^{sp} q^{sq} \right\}.$$

We proved, however, in § 63 that the expression inside the bracket may be written approximately as follows:

$$T_m = \frac{1}{\sqrt{2\pi spq}}.$$

This gives us finally (again using the subscripts):

$$e |\alpha_\nu - sp_0| = 2sp_0q_0T_m = \sqrt{\frac{2sp_0q_0}{\pi}}$$

as the expected value of the absolute deviation in the  $\nu$ th sample set. This same relation evidently holds true for any other of the  $N$  sample sets, which finally gives us the following result for  $\delta$ :

$$\delta = \sqrt{\frac{2}{\pi}} \cdot \sqrt{sp_0q_0}.$$

The dispersion in a Bernoullian series we found before to be of the form:

$$\sigma_B = \sqrt{sp_0q_0}.$$

Hence we have the following relation between the dispersion and the mean deviation:

$$\sigma_B = \sqrt{\frac{\pi}{2}} \delta = 1.2533 \delta.$$

**75. The Lexian Ratio and the Charlier Coefficient of Disturbance.**—The results given in the last few paragraphs may be embodied under the following captions.

1. The mean in a Poisson and Lexis Series is the same as the mean in a Bernoullian Series with constant probability of  $p_0$  in a single trial, where  $p_0$  is defined as above.

2. The dispersion in a Poisson Series is less than the corresponding dispersion in a Bernoullian Series.

3. The dispersion in a Lexis Series is greater than the dispersion in a Bernoullian Series.

The mean and the dispersion of the Bernoullian Series occupy in this connection a central position and may be used as a standard of comparison with other series. This is the method adopted by Lexis in investigating certain statistical series, and we shall return to it in the following chapter. Lexis determines first in a direct manner the dispersion as defined by formula (II) from the statistical data as given by the number sequence  $\alpha$ . This process is known as the direct process (by Lexis called a physical process) and gives a certain dispersion,  $\sigma$ . After this the dispersion is computed by an indirect (combinatorial) process under the assumption that the series follows the Bernoullian distribution. The ratio,  $\sigma : \sigma_B$ , which Charlier calls the *Lexian Ratio* and denotes by the symbol,  $L$ , may now give us an idea about the real nature of the statistical series as represented by the number sequence.

When  $L = 1$ , the series is by Lexis called a *normal* series.

When  $L > 1$ , the series is called *hypernormal*.

When  $L < 1$ , the series is a *subnormal* series.

It is easily seen from the respective formulas that the Poisson Series are subnormal series whereas the Lexian Series are hypernormal. The great majority of statistical series are—as we shall have occasion to see in the following chapter—of a hypernormal kind and correspond thus to the Lexian Series.

In § 74 we found the dispersion in the Lexis series as

$$\sigma_L^2 = \sigma_B^2 + (s^2 - s)\sigma_p^2,$$

where

$$\sigma_p^2 = \frac{\sum(p_v - p_0)^2}{N}.$$

The quantity,  $\sigma_p$ , is the natural measure of the variations in the chances from the mean or normal probability,  $p_0$ . It is

however, dependent on the absolute values of these chances, so that if all chances are changed in the same proportion,  $\sigma_p$  is also changed in the same proportion. Another drawback which influences the Lexian Ratio is the variations of the number  $s$  in each sample set. In order to overcome this difficulty Charlier divides the above quantity  $\sigma_p$  by  $p_0$ . Assuming that the variations in the individual probabilities within each set are of no perceptible influence on the dispersion, we have from the Lexian dispersion:

$$\frac{\sigma_p^2}{p_0^2} = \frac{\sigma^2 - \sigma_B^2}{(s^2 - s)p_0^2}.$$

Neglecting  $s$  in comparison with  $s^2$  and remembering that  $M_B = sp_0$ , we have as an approximation:

$$\frac{\sigma_p}{p_0} = \frac{\sqrt{\sigma^2 - \sigma_B^2}}{M_B} = \rho.$$

Charlier calls the quantity  $100\rho$  the *coefficient of disturbancy* of the statistical series. It is readily seen that the Charlier coefficient is zero in normal series. For hypernormal series it is a positive real quantity whereas for subnormal series  $\rho$  is imaginary.

## CHAPTER XI.

### APPLICATION TO GAMES OF CHANCE AND STATISTICAL PROBLEMS.

**76. Correlate between Theory and Practice.**—In the theoretical analysis just completed we treated the fundamental elementary functions in the theory of probabilities, the probability function, the expected or probable value of a variable quantity, the mean error, the dispersion and the coefficient of disturbancy. The formulas thus derived were founded upon certain hypothetical axioms, which formed the basis of a mathematical a priori probability as defined by Laplace. As far as the purely abstract mathematical analysis is concerned it matters but little if the hypotheses are physically true or not, that is to say, if they agree with physical facts in the universe as it is known to us. A mathematical analysis may be made on the basis of widely divergent hypotheses, a fact which is clearly shown in the Euclidean and Non-Euclidean geometries. It is, however, quite a different matter when we wish to apply our theory to actual phenomena (physical observed events) as it is evident that a correlation between hypothesis and actual facts follows by no means a priori. It is, of course, true that the different hypotheses in the theory of probabilities are derived to greater or less extent from outside sense data. Such sense data, however, give us only the effect and no clue whatsoever to the relation between cause and effect. In the application of our theory every hypothesis—or rather the results derived from such hypothesis—must be verified by actual experience. Before such a verification is made, we advise the reader to be sceptical and not trust too much in the authority of others but follow the sound advice of Chrystal: "In mathematics let no man over-persuade you. Another man's authority is not your reason." We can so much more encourage an attitude of scepticism in view of the fact that even among the leading mathematicians of the present time there exists no uniform opinion as to the truth of the axioms underlying the theory of probabilities.

**77. Homograde and Heterograde Series. Technical Terms.**

—Whenever a common characteristic or attribute of several groups of observed individual objects or events allows a purely quantitative determination, it may be made the subject of a mathematical analysis and in such cases we are often able to make excellent use of the theory of probabilities. Such quantitative measurements may be divided into various domains of classification. Traces of such classification are found in almost every treatise on mathematical statistics but a uniform system nomenclature is unfortunately lacking among the various statisticians and any one reading the modern literature on mathematical statistics notices often various inconsistencies of the different authors. Mr. G. Udny Yule in his excellent treatise "Theory of Statistics" classifies the statistical series into "statistics of attributes" and "statistics of variables." Apart from the fact that Mr. Yule's statistics of variables also is a statistics of attributes—although of different grades—the author apparently ignores the criterion of Lexis and the associated criterion of Charlier. The German writers use the terms "stetige und unstetige Kollektivgegenstand" (continuous and discontinuous collective objects), which were originally introduced by Fechner. Other writers, such as Johannsen of Denmark and Davenport of America, use still other terms. After having made a comparison of the various systems of classification I have in the following decided to adhere to the system of Charlier wherein the observed statistical series are classified as *homograde* and *heterograde*.

If the individuals all possess the same character or attribute in the same grade (intensity)—or if we disregard the different grades of the attributes—such individuals are called *homograde*, and the statistical series thus formed is a *homograde* series. If on the other hand we take into consideration the different varying grades of the attributes observed or measured and form the series accordingly we obtain a *heterograde* series. As examples of *homograde* series we may mention the observed recorded series of coin tossing, card drawings in reference to a specified event, number of births or deaths in a population group, etc. A coin when tossed will either show head or tail, a person will

either be dead or alive. There are no intermediate degrees as for instance that of a half-dead person. In all such series the dividing line between the occurrence of the event (attribute)  $E$  and the occurrence of the opposite event  $\bar{E}$  is distinct and suggests itself a priori and there is no doubt as to the classification of the observed event.

The original record of observation of a homograde series—also known as the *primary list*—is simply a record of the presence or non-presence of a specified attribute of the individuals belonging to the group under observation and is of the following form:

PRIMARY LIST OF HOMOGRADE INDIVIDUALS.

| Symbol for the Individual | Attribute.       |                            |
|---------------------------|------------------|----------------------------|
|                           | Present ( $E$ ). | Non-present ( $\bar{E}$ ). |
| $I_1$                     | 1                |                            |
| $I_2$                     |                  | 1                          |
| $I_3$                     |                  | 1                          |
| $I_4$                     | 1                |                            |
| $I_5$                     | 1                |                            |
| .                         | .                | .                          |
| .                         | .                | .                          |
| .                         | .                | .                          |

In this scheme the individuals  $I_1$ ,  $I_4$  and  $I_5$  possess the attribute  $E$  while the individuals  $I_2$  and  $I_3$  do not have this attribute.

In observing the presence of a specified attribute in a group of individual objects we meet, however, frequently series of quite another nature than the simple homograde series. When investigating the different measures of heights of persons inside a certain population group no simple dichotomous (*i. e.*, cutting in two) division in two opposite and mutually exclusive groups suggests itself a priori. It is of course true that we might divide the total population under observation into two subsidiary groups of *tall* individuals and *short* individuals. But the question then immediately arises, What constitutes a short or a tall person? The answer must necessarily be arbitrary. Persons above the height of 170 cm. may be classed as tall while persons falling short of such measure may be classed as short persons, and we might in this way form a primary homograde table of the form as given above. There is no logical reason, however, to choose the quantity 170 cm. as the dividing line and comparatively

little value would result from such a classification. It is evident that all persons belonging to groups of tall or short are not identical as to the particular attribute in question. The height is merely a characteristic which varies with each individual and no two individuals have mathematically speaking the same height. If we take into consideration the different grades of height among the individuals and arrange the primary table accordingly we obtain a heterograde series of observations. The general form of the primary table of such series is:

PRIMARY LIST OF HETEROGRADE INDIVIDUALS.

| Symbol for the Individual. | Grade of Attribute. |
|----------------------------|---------------------|
| $I_1$                      | $x_1$               |
| $I_2$                      | $x_2$               |
| $I_3$                      | $x_3$               |
| $I_4$                      | $x_4$               |
| $I_5$                      | $x_5$               |
| .                          | .                   |
| .                          | .                   |
| $I_n$                      | $x_n$               |

Here the quantities  $x_1, x_2, \dots, x_n$  give the measures (in kilogram, liter, meter, etc.) of the characteristic in question.<sup>1</sup>

As examples of heterograde series we may mention the lengths, volumes or weights of animals, plants or inorganic objects; astronomical observations as to the brightness of celestial objects; meteorological records of rainfall, temperature or barometer heights; the frequency of deaths among policyholders as to attained age in an assurance company; duration of sickness or disablement, etc.

The investigation of heterograde series is a problem of which we shall treat later under the theory of errors or frequency curves. The homograde series may, however, be explained fully by means of the Bernoullian, Poisson and Lexian Series as founded on the mathematical theory of probabilities in the previous chapters.

**78. Computation of the Mean and the Dispersion in Practice.**—It would be superfluous to enter into a detailed demonstration of the practical calculation of either the mean or the dispersion

<sup>1</sup> It is to be noted that in the homograde series the primary list is given by abstract numbers while the heterograde series consists of concrete numbers.

were it not for the fact that this calculation is performed with a lot of unnecessary and useless labor by the untrained student and even by many professional statisticians. By the ordinary school method the number zero is chosen as the starting point and all the variables are expressed in their absolute magnitudes, *i. e.*, their distance from 0. In this way one often encounters multiplication and addition of large numbers. The Danish biologist and statistician, W. Johannsen, has illustrated the futility of this method in the following example taken from his treatise "Forelæsninger over Læren om Arvelighed" (Copenhagen, 1905).<sup>1</sup> Dr. Petersen, the director of the Danish Biological Station, counted the tail fin rays of 703 flounders (*Pleuronectes*) caught around the neighborhood of the Skaw. The observations follow:

|                   |    |    |    |    |    |    |     |     |     |    |    |    |    |    |    |
|-------------------|----|----|----|----|----|----|-----|-----|-----|----|----|----|----|----|----|
| Number of rays:   | 47 | 48 | 49 | 50 | 51 | 52 | 53  | 54  | 55  | 56 | 57 | 58 | 59 | 60 | 61 |
| No. of flounders: | 5  | 2  | 13 | 23 | 58 | 96 | 134 | 127 | 111 | 74 | 37 | 16 | 4  | 2  | 1  |

The ordinary way of computing the mean would be as follows:

$$[5 \times 47 + 2 \times 48 + 13 \times 49 + \dots + 1 \times 61] \div 703,$$

where 703 is the total number of individuals under observation. In Chapter X we gave the following formula for the mean:

$$M = \frac{m_1 + m_2 + m_3 + \dots + m_N}{N}. \quad (1)$$

This formula may evidently be written as follows:

$$M = \frac{m_1 - M_0 + m_2 - M_0 + m_3 - M_0 + \dots + m_N - M_0}{N} \quad (2)$$

$$+ M_0 = \frac{\Sigma(m_i - M_0)}{N} + M_0 = b + M_0.$$

In this expression  $M_0$ , which Charlier calls the provisional mean, is an arbitrarily chosen number. To show how the introduction of this quantity actually shortens the calculation of the mean we return to the above quoted series of observations of tail fin rays of flounders.

<sup>1</sup> German edition "Elemente der exakten Erblchkeitslehre" (Jena, 1913), page 11.

NUMBER OF RAYS ( $x$ ) IN 703 FLOUNDERS ACCORDING TO OBSERVATIONS OF  
DR. PETERSEN.

$$N = \Sigma F(x) = 703, \quad M_0 = 53.$$

| $x$            | Frequency<br>$= F(x)$ | $x - M_0$ | $(x - M_0)F(x)$ |
|----------------|-----------------------|-----------|-----------------|
| 47             | 5                     | -6        | - 30            |
| 48             | 2                     | -5        | - 10            |
| 49             | 13                    | -4        | - 52            |
| 50             | 23                    | -3        | - 69            |
| 51             | 58                    | -2        | -116            |
| 52             | 96                    | -1        | - 96            |
| 53             | 134                   | +0        | + 0             |
| 54             | 127                   | +1        | +127            |
| 55             | 111                   | +2        | +222            |
| 56             | 74                    | +3        | +222            |
| 57             | 37                    | +4        | +148            |
| 58             | 16                    | +5        | + 80            |
| 59             | 4                     | +6        | + 24            |
| 60             | 2                     | +7        | + 14            |
| 61             | 1                     | +8        | + 8             |
| Sum = $\Sigma$ | 703                   |           | -373 +845       |

We have now:

$$b = (845 - 373) \div 703 = 0.67, \quad M = M_0 + b = 53.67.$$

The method is quite simple and needs hardly any explanation. From a cursory examination of the material we notice that the mean is situated in the neighborhood of the series consisting of 53 rays. We choose therefore the provisional mean,  $M_0$ , as 53. We next form the algebraic differences of  $x - M_0$ . These differences are then multiplied by  $F(x)$ . The algebraic sum of these products divided by  $N = \Sigma F(x)$  gives us the value of  $b$ , which quantity added to  $M_0$  gives the value of the mean,  $M$ .

To show a slightly modified form of the method we take the following observations of coal-mine accidents in Belgium, covering the period 1901-1910, from "Annales des Mines de Belgique." These data I have reduced to a stationary population group of 140,000 mine workers. In other words the quantity  $s$  as defined in § 83 is equal to 140,000.

NUMBER ( $m$ ) OF PERSONS KILLED IN COAL MINE ACCIDENTS IN BELGIUM, 1901-1910.

$$s = 140,000, \quad N = 10, \quad M_0 = 140.$$

| Year.          | $m$ . | $m - M_0$ . | $(m - M_0)^2$ . |
|----------------|-------|-------------|-----------------|
| 1901           | 164   | +24         | 576             |
| 1902           | 150   | +10         | 100             |
| 1903           | 160   | +20         | 400             |
| 1904           | 130   | -10         | 100             |
| 1905           | 127   | -13         | 169             |
| 1906           | 133   | -7          | 49              |
| 1907           | 144   | +4          | 16              |
| 1908           | 150   | +10         | 100             |
| 1909           | 133   | -7          | 49              |
| 1910           | 133   | -7          | 49              |
| Sum = $\Sigma$ |       | -44 +68     | 1608            |

Hence

$$b = (68 - 44) \div 10 = 2.4, \quad M = 140 + 2.4 = 142.4.$$

In this example probably it would have been easier to have formed the sum  $\Sigma m$ , directly and then obtained the mean by division by 10. The actual formation of the algebraic sums of  $m - M_0$  however, greatly facilitates the calculation of the dispersion,  $\sigma$ , to which we now shall turn our attention.

The formula for the dispersion

$$\sigma^2 = \frac{\Sigma(m_v - M)^2}{N} \quad (v = 1, 2, 3, \dots N) \quad (3)$$

may evidently be written as follows:

$$\begin{aligned} \sigma^2 &= \frac{(m_1 - M_0)^2 + (m_2 - M_0)^2 + \dots + (m_N - M_0)^2}{N} - b^2 \\ &= \frac{\Sigma(m_v - M_0)^2}{N} - b^2, \end{aligned} \quad (4)$$

where  $b$  as usual means  $M - M_0$ ,  $M_0$  being the provisional mean. For Belgian coal mine accidents we thus obtain from the above data:

$$\sigma^2 = (1608 \div 10) - 5.76 = 155.04.$$

Where the number of observed individuals is very large an arrangement as that given above for the Belgian statistics becomes too bulky and it is therefore customary to group the observations in classes as for instance in the example of Dr. Johannsen. The dispersion is then computed according to the following elegant

method due to Charlier from whose brochure "Grunddragen af den matematiska Statistiken" ("Rudiments of Mathematical Statistics") I take the following example:

NUMBER OF BOYS ( $m$ ) PER 500 CHILDREN BORN IN 24 PROVINCES OF SWEDEN DURING EACH MONTH IN 1883 AND 1890.

$s = 500$ ,  $N = 576$ ,  $M_0 = 257$ ,  $w = 5$ .

| Class.          |                    |                         |           |             |                 |
|-----------------|--------------------|-------------------------|-----------|-------------|-----------------|
| Limits<br>$m$ . | Number.<br>$= x$ . | Frequency<br>$= F(x)$ . | $xF(x)$ . | $x^2F(x)$ . | $(x+1)^2F(x)$ . |
| 200-204         | -11                | 1                       | - 11      | + 121       | 100             |
| 205-209         | -10                | 0                       | 0         | 0           | 0               |
| 210-214         | - 9                | 0                       | 0         | 0           | 0               |
| 215-219         | - 8                | 1                       | - 8       | + 64        | 49              |
| 220-224         | - 7                | 2                       | - 14      | + 98        | 72              |
| 225-229         | - 6                | 5                       | - 30      | + 180       | 125             |
| 231-234         | - 5                | 13                      | - 65      | + 325       | 208             |
| 235-239         | - 4                | 18                      | - 72      | + 288       | 162             |
| 240-244         | - 3                | 47                      | -141      | + 423       | 188             |
| 245-249         | - 2                | 60                      | -120      | + 240       | 60              |
| 250-254         | - 1                | 81                      | - 81      | + 81        | 0               |
| 255-259         | 0                  | 108                     | 0         | 0           | 108             |
| 260-264         | + 1                | 91                      | + 91      | + 91        | 364             |
| 265-269         | + 2                | 60                      | +120      | + 240       | 540             |
| 270-274         | + 3                | 44                      | +132      | + 396       | 704             |
| 275-279         | + 4                | 22                      | + 88      | + 352       | 550             |
| 280-284         | + 5                | 16                      | + 80      | + 400       | 576             |
| 285-289         | + 6                | 6                       | + 36      | + 216       | 294             |
| 290-294         | + 7                | 0                       | 0         | 0           | 0               |
| 295-299         | + 8                | 0                       | 0         | 0           | 0               |
| 300-304         | + 9                | 1                       | + 9       | + 81        | 100             |
| Sum = $\Sigma$  |                    | 576                     | + 14      | +3596       | +4200           |

The class width interval in the above scheme was chosen as 5. The observed frequencies are given in column 3. We thus find that the greatest frequency of 108 falls in the class interval 255-259. Choosing this class interval as the origin we designate the other class intervals with their proper positive and negative numbers as shown in column 2. The provisional mean,  $M_0$ , is taken as the center of class  $O$ , or  $M_0 = 257$ . In this way the class interval  $w = 5$  is taken as the unit.

The whole calculation is very simple. We first of all form the product  $x \times F(x)$ . The sum of these products divided with  $576 = N$  gives the distance— $b$ —from the provisional mean to the arithmetic mean, expressed in units of the class interval,  $w$ .

We have thus:

$$b = w \times 14 \div 576 = + 0.0243w = + 0.122,$$

or

$$M = 257 + b = 257.12.$$

The formula for the dispersion takes the form

$$\sigma^2 = w^2 \left[ \frac{\Sigma x^2 F(x)}{N} - b^2 \right],$$

where  $b$  is expressed in units of the class interval. The table gives us

$$\Sigma F(x)x^2 = 3596 \quad \text{or}$$

$$\sigma^2 = w^2 [3596 \div 576 - (0.024)^2] = w^2 6.242,$$

$$\sigma = w \times 2.498 = 12.49.$$

Charlier now checks the results by means of the following relation:

$$\Sigma(x+1)^2 F(x) = \Sigma x^2 F(x) + 2\Sigma x F(x) + \Sigma F(x).$$

For the above example we have:

$$\Sigma x^2 F(x) = + 3,596$$

$$2\Sigma x F(x) = + 28$$

$$\Sigma F(x) = + 576$$

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$$\text{Sum} = + 4,200 = \Sigma(x+1)^2 F(x),$$

which proves the accuracy of the calculation.

The full elegance of the Charlier self checking scheme is shown at a later stage under the calculation of the parameters of frequency curves. In the meantime the student may test the advantage of the provisional mean by trying to compute the mean and the dispersion by the conventional school method. A direct computation by this method would in the last example take about a whole day's labor.

Before we proceed to apply the formulas previously demonstrated, we wish to call the attention of the reader to the following important properties of the mean and the dispersion:

1. The algebraic sum of the deviations from the mean—i. e.,  $\Sigma(m_v - M)$ —is zero. This follows immediately from formula (2) of § 78. We have:

$$\check{M} = \frac{\Sigma(m_v - M_0)}{N} + M_0 = b + M_0,$$

where  $M_0$ , the provisional mean, is an arbitrarily chosen number and  $b = \Sigma(m_v - M_0) \div N$ . If  $M_0 \leq M$  we have evidently  $b = 0$ , which proves the statement.

2. The dispersion (standard deviation) is the least possible root-mean-square deviation, *i. e.*, the root-mean-square deviation is a minimum, when the deviations are measured from the mean.

We have (see formula (4)):

$$\sigma^2 = \frac{\Sigma(m_v - M)^2}{N} = \frac{\Sigma(m_v - M_0)^2}{N} - b^2,$$

from which the proposition follows *a fortiori*.

79. Westergaard's Experiments.—The Danish statistician, Harald Westergaard, in his "Statistikens Teori i Grundrids" gives the following results of 10,000 observations divided into 100 equal sample sets of drawings of balls from a bag containing an equal number of red and white balls (the ball was returned to the bag after each drawing):

|            |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
|------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| White:     | 33 | 34 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 |
| Frequency: | 0  | 1  | 1  | 2  | 2  | 2  | 3  | 3  | 4  | 5  | 6  | 5  | 11 | 9  | 5  | 10 | 4  | 8  |
| White:     | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |    |    |    |    |    |    |    |    |    |
| Frequency: | 3  | 5  | 4  | 4  | 0  | 0  | 1  | 1  | 1. |    |    |    |    |    |    |    |    |    |

The elements as resulting from Westergaard's drawings clearly represent a Bernoullian Series where the number of comparison  $s$  is equal to 100. Arranging the data in classes—taking 3 as the class interval—the computation of the mean and the dispersion is easily performed by means of the Charlier self checking scheme.

BERNOULLIAN SERIES. NUMBER OF WHITE BALLS IN 100 DRAWINGS (WESTERGAARD).

| $s = 100, N = 100, M_0 = 49, w = 3.$ |      |         |          |            |                |
|--------------------------------------|------|---------|----------|------------|----------------|
| $m.$                                 | $z.$ | $F(z).$ | $zF(z).$ | $z^2F(z).$ | $(z+1)^2F(z).$ |
| 33-35                                | -5   | 1       | -5       | 25         | 16             |
| 36-38                                | -4   | 0       | 0        | 0          | 0              |
| 39-41                                | -3   | 5       | -15      | 45         | 20             |
| 42-44                                | -2   | 8       | -16      | 32         | 8              |
| 45-47                                | -1   | 15      | -15      | 15         | 0              |
| 48-50                                | 0    | 25      | 0        | 0          | 25             |
| 51-53                                | +1   | 19      | +19      | 19         | 76             |
| 54-56                                | +2   | 16      | +32      | 64         | 144            |
| 57-59                                | +3   | 8       | +24      | 72         | 128            |
| 60-62                                | +4   | 2       | +8       | 32         | 50             |
| 63-65                                | +5   | 1       | +5       | 25         | 36             |
| Sum                                  |      | 100     | (-51+88) | 329        | 503            |

✓  
CONTROL CHECK.

$$\Sigma x^2 F(x) = 329$$

$$2\Sigma x F(x) = 74$$

$$\Sigma F(x) = 100$$

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$$\text{Sum} = 503 = \Sigma(x+1)^2 F(x)$$

$$b = w(88 - 51) : 100 = w \times 0.37 = 1.11,$$

$$\text{or } M = M_0 + b = 50.11,$$

$$\sigma^2 = w^2[329 : 100 - b^2]^1 = w^2(3.29 - 0.137) = 28.377,$$

$$\text{or } \sigma = 5.33.$$

Giving due allowance for the respective mean errors of the mean and the deviation we have finally:<sup>2</sup>

$$M = 50.11 \pm 0.536, \quad \sigma = 5.33 \pm 0.378.$$

We shall now compare these values with the corresponding theoretical values of the Bernoullian series. The a priori probabilities of drawing red and white are in this example  $p = q = \frac{1}{2}$ . Hence we have as the theoretical values for the mean and the dispersion:

$$M_B = 100 \times \frac{1}{2} = 50, \quad \sigma_B = \sqrt{100 \times \frac{1}{2} \times \frac{1}{2}} = 5.$$

A comparison between the observed and the theoretical ideal values—taking into account the proper mean errors—shows a very close agreement as far as the dispersion is concerned while the difference in the mean is about  $\frac{1}{2}$  of the mean error. A computation of the Lexian Ratio and the Charlier Coefficient of Disturbancy yields the following results:

$$L = 1.072; \quad 100\rho = 3.68.$$

Taking into account the proper mean errors due entirely to the *fluctuation of sampling* we find, however, that our theoretical results and formulas of the previous chapters have been verified in an absolutely satisfactory manner.

**80. Charlier's Experiments.**—In the above mentioned brochure, "Grunddragen," Charlier gives the results of a long series of card drawings illustrating the Bernoullian, the Poisson and the Lexian Series. As an example showing the frequency dis-

<sup>1</sup>  $b$  is expressed in units of  $w$ .

<sup>2</sup> For mean errors of  $M$  and  $\sigma$  see Addenda.

tribution in a Bernoullian Series Charlier made 10,000 individual drawings (with replacements) from an ordinary whist deck and recorded the number of black and red cards drawn in this manner. Arranging the drawings in sample sets of 10 individual drawings, M. Charlier gives the following table:

BERNOULLIAN SERIES. NUMBER ( $m$ ) OF BLACK CARDS IN SAMPLE SETS OF 10.

| $s = 10, N = 1,000, M_0 = 5, w = 1.$ |      |         |          |            |                |
|--------------------------------------|------|---------|----------|------------|----------------|
| $m.$                                 | $z.$ | $F(z).$ | $zF(z).$ | $z^2F(z).$ | $(z+1)^2F(z).$ |
| 0                                    | -5   | 3       | - 15     | + 75       | + 48           |
| 1                                    | -4   | 10      | - 40     | + 160      | + 90           |
| 2                                    | -3   | 43      | -129     | + 387      | + 172          |
| 3                                    | -2   | 116     | -232     | + 464      | + 116          |
| 4                                    | -1   | 221     | -221     | + 221      | 0              |
| 5                                    | 0    | 247     | 0        | 0          | + 247          |
| 6                                    | +1   | 202     | +202     | + 202      | + 808          |
| 7                                    | +2   | 115     | +230     | + 460      | +1,035         |
| 8                                    | +3   | 34      | +102     | + 306      | + 544          |
| 9                                    | +4   | 9       | + 36     | + 144      | + 225          |
| 10                                   | +5   | 0       | 0        | 0          | 0              |
| Sum:                                 |      | 1,000   | - 67     | +2,419     | +3,285         |

CONTROL CHECK.

$$\Sigma^2 xF(x) = + 2,419$$

$$2\Sigma xF(x) = - 134$$

$$\Sigma F(x) = + 1,000$$

$$\text{Sum} = + 3,285 = \Sigma(x+1)^2F(x)$$

From the above values we obtain:

$$b = - 67 : 1,000 = -.067; \sigma^2 = 2,419 : 1,000 - b^2 = 2.415.$$

Making due allowance for mean errors we have thus:

$$M = 5 - 0.067 = 4.933 \pm 0.050; \sigma = 1.554 \pm 0.035.$$

For the theoretical mean and dispersion we obtain the following values: ( $p = q = \frac{1}{2}$ )

$$M_B = 5; \sigma_B = 1.581,$$

which gives the following values for the Lexian Ratio and the Charlier coefficient:

$$L = .983, 100\rho \text{ is imaginary.}$$

These results would indicate a slightly subnormal series. Taking into account the fluctuations due to sampling and for which the

mean error serves as a measure the results become normal and serve again as a verification of the theory.

*Poisson Series.*—As an illustration of the frequency distribution in a Poisson Series Charlier made the following experiment: From an ordinary whist deck was drawn a single card and the color noted. Before the second drawing a spade was eliminated from the deck and replaced by a heart from another deck of cards, so that the deck then contained 12 spades, 13 clubs, 13 diamonds and 14 hearts; from this deck another card was drawn and the color noted. Then another spade was eliminated and a heart substituted. From this deck, containing 11 spades, 13 clubs, 13 diamonds and 15 hearts, a card was again drawn. The drawings were in this manner continued until all the spades were replaced by hearts. The same operation was applied to the clubs, which were replaced by diamonds. After 27 drawings the deck contained only red cards. Altogether 100 sample sets of 27 drawings were made with the following results:

POISSON SERIES. NUMBER ( $m$ ) OF BLACK CARDS IN SAMPLE SETS OF 27.

$s = 27, N = 100, M_0 = 7, w = 1.$

| $m.$ | $z.$ | $F(z).$ | $zF(z).$ | $z^2F(z).$ | $(z+1)^2F(z).$ | Control Check. |
|------|------|---------|----------|------------|----------------|----------------|
| 3    | -4   | 2       | -8       | +32        | 18             |                |
| 4    | -3   | 6       | -18      | +54        | 24             | +378           |
| 5    | -2   | 14      | -28      | +56        | 14             | +32            |
| 6    | -1   | 14      | -14      | +14        | 0              | +100           |
| 7    | 0    | 22      | 0        | 0          | 22             |                |
| 8    | +1   | 17      | +17      | +17        | 68             | +510           |
| 9    | +2   | 14      | +28      | +56        | 126            |                |
| 10   | +3   | 8       | +24      | +72        | 128            |                |
| 11   | +4   | 1       | +4       | +16        | 25             |                |
| 12   | +5   | 1       | +5       | +25        | 36             |                |
| 13   | +6   | 1       | +6       | +36        | 49             |                |
| Sum: |      | 100     | +16      | +378       | 510            |                |

The calculation of the mean and the dispersion with their respective mean errors yields the following result:

$$b = +0.16, \quad M = 7.16 \pm 0.211,$$

$$\sigma^2 = 3.78 - (0.16)^2 = 3.754, \quad \sigma = 1.937 \pm 0.149.$$

The theoretical Poisson values according to the formulas of § 67 are:

$$M_p = 6.75, \quad \sigma_p = 2.111.$$

If we now take the arithmetic mean of the various proba-

bilities of drawing a black card we find that  $p_0 = \frac{1}{4}$ . If all the drawings had been performed with a constant probability we should according to the Bernoullian scheme have:

$$M_B = 27 \times \frac{1}{4} = 6.75, \quad \sigma_B = \sqrt{27 \times \frac{1}{4} \times \frac{3}{4}} = 2.25.$$

These results verify the formulas as obtained under the discussion of the Poisson Series. ( $M_P = M_B$ ,  $\sigma_P < \sigma_B$ .)

*Lexian Series.*—In testing the Lexian Series Charlier first took 10 samples of 10 individual drawings in each sample from an ordinary whist deck. The number of black cards thus drawn was recorded. After this, 10 samples of the same magnitude were taken from a deck containing 25 black and 27 red cards; and then 10 samples from a deck with 24 black and 28 red cards. Of the total 270 samples (until the deck contains only red cards) Charlier gives the first 100 which gave the following result:

| LEXIAN SERIES. NUMBER ( $m$ ) OF BLACK CARDS IN 10 DRAWINGS. |      |         |         |            |                |                |
|--------------------------------------------------------------|------|---------|---------|------------|----------------|----------------|
| $s = 10, N = 100, M_0 = 4.$                                  |      |         |         |            |                |                |
| $m.$                                                         | $z.$ | $F(z).$ | $zF(z)$ | $z^2F(z).$ | $(z+1)^2F(z).$ | Control Check. |
| 1                                                            | -3   | 4       | -12     | + 36       | + 16           |                |
| 2                                                            | -2   | 9       | -18     | + 36       | + 9            |                |
| 3                                                            | -1   | 19      | -19     | + 19       | + 0            |                |
| 4                                                            | 0    | 21      | 0       | 0          | + 21           |                |
| 5                                                            | +1   | 23      | +23     | + 23       | + 92           |                |
| 6                                                            | +2   | 10      | +20     | + 40       | + 90           | +294           |
| 7                                                            | +3   | 12      | +36     | +108       | +192           | + 76           |
| 8                                                            | +4   | 2       | + 8     | + 32       | + 50           | +100           |
| Sum:                                                         |      | 100     | +38     | +294       | +470           | +470           |

The final computations (with mean errors) give:

$$b = + 0.38, \quad M = 4.38 \pm 0.167,$$

$$\sigma^2 = 294 : 100 - b^2 = + 2.796, \quad \sigma = + 1.672 \pm 0.118.$$

The mean probability in all trials was:

$$p_0 = 21.50 : 52 = 0.4135, \quad \text{or} \quad M_B = sp_0 = 4.135,$$

$$\sigma_B = \sqrt{sp_0q_0} = 1.557.$$

A calculation of the mean and the dispersion according to the formulas under the Lexian Series (see § 74) gives according to Charlier:

$$M_L = 4.135, \quad \sigma_L = 1.643.$$

This shows that the dispersion in a Lexian Series is greater than the corresponding Bernoullian dispersion. The Lexian Ratio:  $L = \sigma_L : \sigma_B$  has the value 1.06. The series according to the terminology of Lexis has a hypernormal dispersion, although a very small one. Charlier in "Grunddragen" (§ 30) says that when arranging the material in 27 samples, each sample containing 100 single trials, the Lexian Ratio has the value  $L=3.82$ , indicating a greater hypernormal dispersion than in the smaller samples.

**81. Experiments by Bonynge and Fisher.**—As an additional verification of the Bernoullian, Poisson and Lexian Series my co-editor, Mr. Bonynge, and myself have repeated the experiments of Westergaard and Charlier in a slightly modified form.

*Bernoullian Series.*—In 20 sample sets, each set containing 500 individual drawings, from an ordinary whist deck, I counted the number of diamonds drawn in each sample. My records gave the following scheme:

BERNOULLIAN SERIES. NUMBER OF DIAMONDS ( $m$ ) IN 20 SAMPLE SETS OF

500 DRAWINGS.  
 $s = 500, N = 20, M_0 = 125.$

| $m$ . | $m - M_0$ | $(m - M_0)^2$ |
|-------|-----------|---------------|
| 123   | - 2       | 4             |
| 143   | + 18      | 324           |
| 124   | - 1       | 1             |
| 133   | + 8       | 64            |
| 142   | + 17      | 289           |
| 130   | + 5       | 25            |
| 117   | - 8       | 64            |
| 122   | - 3       | 9             |
| 132   | + 7       | 49            |
| 109   | -16       | 256           |
| 130   | + 5       | 25            |
| 139   | + 14      | 196           |
| 138   | + 13      | 169           |
| 129   | + 4       | 16            |
| 136   | + 11      | 121           |
| 121   | - 4       | 16            |
| 135   | + 10      | 100           |
| 124   | - 1       | 1             |
| 135   | + 10      | 100           |
| 116   | - 9       | 81            |
| Sum:  | -44 +122  | 1,910         |

The results with their respective mean errors are as follows:

$$M = 128.9 \pm 2.01, \quad \sigma = 8.962 \pm 1.416$$

The theoretical Bernoullian mean and the dispersion have the values:

$$M_B = 125, \quad \sigma_B = \sqrt{spq} = \sqrt{500 \times \frac{1}{4} \times \frac{3}{4}} = 9.682,$$

where  $p = \frac{1}{4}$  denotes the a priori probability of drawing a diamond.

Again I counted the number of aces (irrespective of color) which appeared in 100 sample sets of 100 individual drawings from the same deck of cards. The records arranged in classes gave the following scheme:

NUMBER OF ACES ( $m$ ) IN 100 SAMPLE SETS OF 100 INDIVIDUAL DRAWINGS.

| $s = 100, N = 100, M_0 = 8, w = 1.$ |    |         |          |            |                  |               |
|-------------------------------------|----|---------|----------|------------|------------------|---------------|
| m.                                  | z. | $F(z).$ | $zF(z).$ | $z^2F(z).$ | $(z + 1)^2F(z).$ | Control Check |
| 2                                   | -6 | 1       | - 6      | 36         | 25               |               |
| 3                                   | -5 | 8       | -40      | 200        | 128              |               |
| 4                                   | -4 | 8       | -32      | 128        | 72               |               |
| 5                                   | -3 | 7       | -21      | 53         | 28               |               |
| 6                                   | -2 | 9       | -18      | 36         | 9                |               |
| 7                                   | -1 | 21      | -21      | 21         | 0                |               |
| 8                                   | 0  | 13      | 0        | 0          | 13               |               |
| 9                                   | +1 | 15      | +15      | 15         | 60               |               |
| 10                                  | +2 | 3       | + 6      | 12         | 27               |               |
| 11                                  | +3 | 9       | +27      | 81         | 144              | +811          |
| 12                                  | +4 | 1       | + 4      | 16         | 25               | -110          |
| 13                                  | +5 | 2       | +10      | 50         | 72               | +100          |
| 14                                  | +6 | 2       | +12      | 72         | 98               |               |
| 15                                  | +7 | 0       | + 0      | 0          | 0                | 801           |
| 16                                  | +8 | 0       | + 0      | 0          | 0                |               |
| 17                                  | +9 | 1       | + 9      | 81         | 100              |               |
| Sum:                                |    | 100     | -55      | 811        | 801              |               |

$$b = -55 : 100 = -0.55,$$

$$M = M_0 + b = 7.45 \pm 0.279 \text{ (with mean error),}$$

$$\sigma^2 = w^2 \frac{\sum x^2 F(x)}{\sum F(x)} - b^2 = 7.8075,$$

or

$$\sigma = 2.794 \pm 0.198 \text{ (with mean error).}$$

The theoretical Bernoullian values are:

$$M_B = 100 \times \frac{1}{4} = 7.69, \quad \sigma_B = \sqrt{100 \times \frac{1}{4} \times \frac{3}{4}} = 2.663.$$

A comparison between the empirical and the theoretical a priori values exhibits a close correspondence.

*Poisson Series.*—As an illustration of the Poisson Series Mr. Bonynge made the following experiment. A sample set of 20 single drawings of balls from an urn (one ball being drawn at a time) was made under the following conditions:

In drawing No. 1 the urn contained 20 white and 20 black balls.  
 " " " 2 " " " 21 " " 19 " "  
 " " " 3 " " " 22 " " 18 " "  
 . . . . .  
 " " " 20 " " " 39 " " 1 " "

Altogether Bonynge took 500 sample sets which arranged in classes give the following scheme:

POISSON SERIES. NUMBER OF BLACK BALLS ( $m$ ) IN 500 SAMPLE SETS OF 20 INDIVIDUAL DRAWINGS (BONYNGE).

$$s = 20, \quad N = 500, \quad M_0 = 5.$$

| $m$ . | $z$ .      | $F(z)$ . | $zF(z)$ . | $z^2F(z)$ . | $(z+1)^2F(z)$ . |
|-------|------------|----------|-----------|-------------|-----------------|
| 0     | -5         | 2        | -10       | 50          | 32              |
| 1     | -4         | 9        | -36       | 144         | 81              |
| 2     | -3         | 35       | -105      | 315         | 140             |
| 3     | -2         | 52       | -104      | 208         | 52              |
| 4     | -1         | 86       | -86       | 86          | 0               |
| 5     | 0          | 109      | 0         | 0           | 109             |
| 6     | +1         | 85       | +85       | 85          | 340             |
| 7     | +2         | 69       | +138      | 276         | 621             |
| 8     | +3         | 30       | +90       | 270         | 480             |
| 9     | +4         | 16       | +64       | 256         | 400             |
| 10    | +5         | 6        | +30       | 150         | 216             |
| 11    | +6         | 1        | +6        | 36          | 49              |
| Sum:  | $\Sigma =$ | 500      | + 72      | 1876        | 2520            |

Hence we have:

$$b = 0.144, \quad M = 5.144, \quad \sigma^2 = 3.732, \quad \sigma = 1.932.$$

The theoretical Poisson values are:

$$M_P = 5.25, \quad \sigma_P = 1.86 \text{ (see formulas, § 74).}$$

The mean of the various probabilities of drawing a black ball is  $p_0 = \frac{2}{3}$ . According to the Bernoullian scheme we should then have the following values for the mean and the dispersion:

$$M_B = 20 \times \frac{2}{3} = 5.25, \quad \sigma_B = (20 \times \frac{2}{3} \times \frac{1}{3})^{\frac{1}{2}} = 1.968.$$

These values confirm the Poisson theorems ( $M_P = M_B, \sigma_P < \sigma_B$ ).

*Lexian Series.*—As additional illustration of the Lexian Series

I took 20 sample sets, each set containing 500 drawings of a single ball from an urn (with replacements). The contents of the urn varied from set to set as follows:

Sample set No. 1 : 20 white and 20 black balls.  
 " " " 2 : 21 " " 19 " "  
 " " " 3 : 22 " " 18 " "  
 . . . . .  
 " " " 20 : 39 " " 1 " "

In the 21st set all the black balls were eliminated and the urn contained white balls only. This set, however, was not taken in consideration in calculating the mean and the dispersion.

LEXIAN SERIES. NUMBER ( $m$ ) OF BLACK BALLS IN 20 SAMPLE SETS OF 500 INDIVIDUAL DRAWINGS (FISHER).

$s = 500$ ,  $N = 20$ ,  $M_0 = 130$ .

| No. of Set. | $m$ .      | $(m - M_0)$ . | $(m - M_0)^2$ . |
|-------------|------------|---------------|-----------------|
| 1           | 251        | + 121         | 14641           |
| 2           | 246        | + 116         | 13456           |
| 3           | 222        | + 92          | 8464            |
| 4           | 216        | + 86          | 7396            |
| 5           | 193        | + 63          | 3969            |
| 6           | 176        | + 46          | 2116            |
| 7           | 183        | + 53          | 2809            |
| 8           | 173        | + 43          | 1849            |
| 9           | 156        | + 26          | 676             |
| 10          | 135        | + 5           | 25              |
| 11          | 140        | + 10          | 100             |
| 12          | 127        | - 3           | 9               |
| 13          | 115        | - 15          | 225             |
| 14          | 96         | - 34          | 1156            |
| 15          | 78         | - 52          | 2704            |
| 16          | 69         | - 61          | 3721            |
| 17          | 55         | - 75          | 5625            |
| 18          | 43         | - 87          | 7569            |
| 19          | 29         | - 101         | 10201           |
| 20          | 19         | - 111         | 12321           |
| Sum:        | $\Sigma =$ | $- 539 + 661$ | 99012           |

$$b = (661 - 539):20 = 6.6, \quad M = M_0 + b = 136.6 \pm 15.86.$$

$$\sigma^2 = 99012:20 - b^2 = 4913.4, \quad \sigma = 70.098 \pm 11.09 \text{ (with mean errors).}$$

The theoretical Lexian values are:

$$M_L = 131.25, \quad \sigma_L = 72.676 \text{ (see § 74).}$$

If the series represented a true Bernoullian Series, we should have

$$M_B = 500 \times \frac{21}{80} = 131.25, \quad \sigma_B = \sqrt{500 \times \frac{21}{80} \times \frac{59}{80}} = 9.839.$$

These values confirm the Lexian Theorem ( $M_L = M_B, \sigma_L > \sigma_B$ ).

A computation of the Charlier Coefficient of Disturbancy from the observed values gives :

$$100_p = 50.80$$

whereas the theoretical value is 55.38, showing a decidedly hypernormal dispersion, a result which was to be expected since the probabilities of drawing black varies from  $\frac{1}{2}$  to  $\frac{1}{4}$  in the various sets of samples.

All the above experiments show a completely satisfactory verification of the various theorems of the previous chapters and may perhaps serve as a vindication of the followers of Laplace, who like him hold that an *a priori* foundation for probability judgments is indispensable.

## CHAPTER XII.

### CONTINUATION OF THE APPLICATION OF THE THEORY OF PROBABILITIES TO HOMOGRADE STATISTICAL SERIES.

**82. General Remarks.**—In this chapter it is our intention to discuss the application of the theory of probabilities to homograde statistical series with special reference to vital statistics. We owe the reader an apology, however, inasmuch as in the former paragraphs we have employed the term *statistics* without defining its meaning in a rigorous manner. A definition may perhaps appear superfluous since statistics nowadays is almost a household word. The term unfortunately is often employed as a mere phrase without any understanding of its real meaning. This applies especially to that band of self-styled statisticians, mere dilettanti, who, with an energy which undoubtedly could be better employed otherwise, attempt to investigate and analyze mass phenomena regardless of method and system. When investigations are undertaken by such dilettanti the common gibe that “statistics will prove anything” becomes, alas, only too true and proves at least that “like other mathematical tools they can be wielded effectively only by those who have taken the trouble to understand the way they work.”<sup>1</sup>

*By the science of statistics we understand the recording and subsequent quantitative analysis of observed mass phenomena.*

*By mathematical statistics (also called statistical methods) we understand the quantitative determination and measurement of the effect of a complex of causes acting on the object under investigation as furnished by previously recorded observations as to certain attributes among a collective body of individual objects.*

Practical statistics—if such a name may be used—then simply becomes the mechanical collection of statistical data, i. e., the recording of the observed attributes of each individual. In no way do we wish to underestimate the importance of this process

<sup>1</sup> See Nunn, “Exercises in Algebra” (London, 1914), pages 432–33.

which is as important for the statistical analysis as is the gathering of structural materials for the erection of a large building.

Mathematical statistics is thus the tool we must use in the final analysis of the statistical data. It is a very effective and powerful tool when used properly by the investigator. At the same time it is not an automatic calculating machine in which we need only put the material and read off the result on a dial. A person without any knowledge whatsoever about the nature of logarithms may in a few hours be taught how to use a logarithmic table in practical computations, but it would be foolish to view the formulas and criteria from probabilities when applied to statistical data in the same light as a table of logarithms in calculating work. Such formulas and criteria must be used with caution and discretion and only by those who have taken the trouble to make a thorough study of probabilities and master their real meaning and their relation to mass phenomena. If put in the hands of mere amateurs the formulas become as dangerous a toy as a razor to a child.

It is not our intention to give in this work a description of the technique of the collection of the material, which depends to a large extent on local social conditions and for which it is difficult to give a set of fixed rules. In the following we shall treat the mathematical methods of statistics exclusively, and furthermore make the theory of probabilities the basis of our investigations.

**83. Analogy between Statistical Data and Mathematical Probabilities.**—Let us for the moment imagine a closed community with a stationary population from year to year and let us denote the size of such a population by  $s$ . Let us furthermore suppose we were given a series of numbers:

$$m_1, m_2, m_3, \dots m_N,$$

denoting the number of children born in various years in this community. The ratios

$$\frac{m_1}{s}, \frac{m_2}{s}, \frac{m_3}{s}, \dots \frac{m_N}{s}$$

may then be looked upon as probabilities of a childbirth in various years. As Charlier justly remarks, "such an identification of a statistical ratio with a mathematical probability is

at first sight a mere analogy which possibly may have very little in common with the observed statistical phenomena, but a closer scrutiny shows the great importance for statistics of such a view." If such ratios could be regarded as mathematical probabilities wherein the various  $m$ 's were identical to favorable cases in  $s$  total trials, the mean and the dispersion could be determined a priori from the Bernoullian Theorem. The founders of mathematical statistics regarded the identification of an ordinary statistical series with a Bernoullian Series almost as axiomatic. This view is found even among some leading writers of the present time. Among others we apparently find this traditional view by the eminent English actuary, G. King, in his classic "Text Book." In Chapter II of this well-known standard actuarial treatise a probability is defined as follows: "If an event may happen in  $\alpha$  ways and fail in  $\beta$  ways, all these ways being equally likely, the probability of the happening of the event is  $\alpha \div (\alpha + \beta)$ ." With this definition as a basis King then deduces the elementary formulas of the addition and multiplication theorems. He then continues: "Passing now to the mortality table, if there be  $l_x$  persons living at age  $x$ , and if these  $l_{x+n}$  survive to age  $x + n$ , then the probability that a life aged  $x$  will survive  $n$  years is  $l_{x+n} \div l_x = {}_n p_x$ . And again "the probability that a life aged  $x$  and a life aged  $y$  will both survive  $n$  years is  ${}_n p_x \times {}_n p_y$ ."<sup>1</sup> From the above it would appear that the author unreservedly assumes a one-to-one correspondence between the  $l_{x+n}$  survivors and "favorable ways" as known from ordinary games of chance and a similar correspondence between the original  $l_x$  persons and "equally possible cases." A simple consideration will show that there exists no a priori reason for such a unique correspondence between ordinary empirical death rates and mathematical probabilities. None of the original  $l_x$  persons can be considered as

<sup>1</sup> Mr. H. Moir in his "Primer of Insurance" tried to avoid the difficulty by giving a wholly new definition of "equally likely events." According to Moir "events may be said to be 'equally likely' when they recur with regularity in the long run." Apart from the half metaphorical term "in the long run" Mr. Moir fails to state what he means by the expression "with regularity." If the statement is to be understood as regular repetitions of a certain event in various sample sets, it is evident that we may obtain a regular recurrence of the observed absolute frequencies in a Poisson Series, where—as we know—the events are not equally likely."—A.F.

being "equally likely" as in the sense of games of chance. Numerous factors such as heredity, environment, climatic and economic conditions, etc., play here a vital part in the various complexes embracing the original  $l_x$  persons.

The belief in an absolute identity of mathematical probabilities and statistical frequency ratios seems to have originated from Gauss. The great German mathematician—or rather the dogmatic faith in his authority as a mathematician—proved thus for a number of years a veritable stumbling block to a fruitful development of mathematical statistics. Gauss and his followers maintained that all statistical mass phenomena could be made to conform with the law of errors as exhibited by the so-called Gaussian Normal Error Curve. If certain statistical series exhibited discrepancies they claimed that such deviations arose from the limited number of observations. The deviations would become less marked if the number of observed values was enlarged and would eventually disappear as the number of observations approached infinity as its ultimate value. The Gaussian dogma held sway despite the fact that the Danish actuary, Oppermann, and the French mathematicians, Binemaye and Cournot, have pointed out that several statistical series, despite all efforts to the contrary offered a persistent defiance to the Gaussian law. The first real attack on the dogma laid down so authoritatively by Gauss was delivered by the French actuary, Dormay, in certain investigations relating to the French census. It was, however, first after the appearance of the already mentioned brochure by Lexis, "Die Massenerscheinungen, etc.," that a correct idea was gained about the real nature of statistical series.

The Lexian theory was expounded in the previous chapters of this work, and we are therefore ready to enter upon the investigations of a few selected mass observations from the domain of vital statistics.

**84. Number of Comparison and Proportional Factors.**—In the mathematical treatment of the Lexian theory of dispersion we tacitly assumed that the total number of individual trials in a sample set or the number of comparison,  $s$ , remained constant from set to set. In the observations on games of chance ~~is~~

remained in our power to arrange the actual experiments in such a manner that  $s$  would be constant. In actual social statistical series such simple conditions do not exist. In comparing the number of births in a country with the total population it is readily noticed that the population does not remain constant but varies from year to year. For this reason the various numbers  $m$  denoting the births are not directly comparable with another. We may, however, easily form a new series of the form:

$$\frac{s}{s_1} \cdot m_1, \frac{s}{s_2} \cdot m_2, \frac{s}{s_3} \cdot m_3, \dots \frac{s}{s_N} \cdot m_N,$$

wherein the various numbers,  $m_1, m_2, m_3, \dots$ , corresponding to the numbers of comparison  $s_1, s_2, s_3, \dots$ , are reduced to a constant number of comparison  $s$ . This series is by Charlier called a *reduced statistical series*. Such a reduction requires, in many

PROPORTIONAL FACTORS FOR A HYPOTHETICAL STATIONARY POPULATION IN  
SWEDEN AND DENMARK EQUAL TO 5,000,000 AND 2,500,000  
RESPECTIVELY.

| Year. | Sweden,<br>Inhabitants. | $s: s_k$ . | Year. | Denmark,<br>Inhabitants. | $s: s_k$ . |
|-------|-------------------------|------------|-------|--------------------------|------------|
| 1876  | 4,429,713               | 1.1288     | 1888  | 2,143,000                | 1.1666     |
| 1877  | 4,484,542               | 1.1150     | 89    | 2,161,000                | 1.1569     |
| 1878  | 4,531,863               | 1.1033     | 1890  | 2,179,000                | 1.1473     |
| 79    | 4,578,901               | 1.0919     | 91    | 2,195,000                | 1.1390     |
| 1880  | 4,565,668               | 1.0952     | 92    | 2,210,000                | 1.1312     |
| 81    | 4,572,245               | 1.0936     | 93    | 2,226,000                | 1.1230     |
| 82    | 4,579,115               | 1.0919     | 94    | 2,248,000                | 1.1121     |
| 83    | 4,603,595               | 1.0861     | 1895  | 2,276,000                | 1.0984     |
| 84    | 4,644,448               | 1.0765     | 96    | 2,306,000                | 1.0841     |
| 1885  | 4,682,769               | 1.0677     | 97    | 2,338,000                | 1.0694     |
| 86    | 4,717,189               | 1.0600     | 98    | 2,371,000                | 1.0544     |
| 87    | 4,734,901               | 1.0560     | 99    | 2,403,000                | 1.0404     |
| 88    | 4,748,257               | 1.0530     | 1900  | 2,432,000                | 1.0280     |
| 89    | 4,774,409               | 1.0472     | 01    | 2,462,000                | 1.0154     |
| 1890  | 4,784,981               | 1.0449     | 02    | 2,491,000                | 1.0036     |
| 91    | 4,802,751               | 1.0410     | 03    | 2,519,000                | 0.9925     |
| 92    | 4,806,865               | 1.0402     | 04    | 2,546,000                | 0.9819     |
| 93    | 4,824,150               | 1.0365     | 1905  | 2,574,000                | 0.9713     |
| 94    | 4,873,183               | 1.0261     | 06    | 2,603,000                | 0.9604     |
| 1895  | 4,919,260               | 1.0165     | 07    | 2,635,000                | 0.9488     |
| 96    | 4,962,568               | 1.0076     | 08    | 2,668,000                | 0.9370     |
| 97    | 5,009,632               | 0.9981     | 09    | 2,702,000                | 0.9252     |
| 98    | 5,062,918               | 0.9875     | 1910  | 2,737,000                | 0.9134     |
| 1899  | 5,097,402               | 0.9809     | 11    | 2,800,000                | 0.8929     |
| 1900  | 5,136,441               | 0.9734     | 1912  | 2,830,000                | 0.8834     |

cases, a certain correction. However, when the general ratios  $s \div s_k$  ( $k = 1, 2, 3 \dots N$ ) are close to unity the reduced series may be treated as a directly observed series. In most of the following examples taken from Scandinavian statistical tabular works the *proportional factor*  $s \div s_k$ , is close to unity as shown in the table below. For Sweden I have, following Charlier, assumed a stationary population  $s = 5,000,000$ . The corresponding Danish  $s$  I have taken as 2,500,000.

The above figures are taken from "Sveriges officiella statistik" and "Statistisk Aarbog for Danmark" for 1913 (Précis de Statistique, 1913).

85. Child Births in Sweden.—From Charlier's "Grunddragen" I select the following example showing the number of children born in Sweden in the period from 1881-1900 as reduced to a stationary population of 5,000,000.

NUMBER OF CHILDREN BORN IN SWEDEN AS TO CALENDAR YEAR (CHARLIER).  
 $s = 5,000,000$ ,  $N = 20$ ,  $M_0 = 140,000$ .

| Year.                            | $m$ .   | $m - M_0$ . | $(m - M_0)^2$ . |
|----------------------------------|---------|-------------|-----------------|
| 1881                             | 145,230 | +5,230      | 27,352,900      |
| 82                               | 146,630 | +6,630      | 44,089,600      |
| 83                               | 144,320 | +4,320      | 18,662,400      |
| 84                               | 149,360 | +9,360      | 87,609,600      |
| 1885                             | 146,600 | +6,600      | 43,560,000      |
| 86                               | 148,270 | +8,270      | 68,392,900      |
| 87                               | 148,020 | +8,020      | 64,320,400      |
| 88                               | 143,680 | +3,680      | 13,542,400      |
| 89                               | 138,300 | -1,700      | 2,890,000       |
| 1890                             | 139,600 | - 400       | 160,000         |
| 91                               | 141,070 | +1,070      | 1,144,900       |
| 92                               | 134,830 | -5,170      | 26,728,900      |
| 93                               | 136,540 | -3,460      | 11,971,600      |
| 94                               | 134,840 | -5,160      | 26,625,600      |
| 1895                             | 136,820 | -3,180      | 10,112,400      |
| 96                               | 135,330 | -4,670      | 21,808,900      |
| 97                               | 132,750 | -7,250      | 52,562,500      |
| 98                               | 134,820 | -5,180      | 26,832,400      |
| 99                               | 131,320 | -8,680      | 75,342,400      |
| 1900                             | 134,460 | -5,540      | 30,691,600      |
| Sum $\Sigma = + 53,190 - 50,390$ |         |             | 654,401,400     |

From which we obtain:

$$b = (+ 53,190 - 50,390) : 20 = 140$$

$$M = M_0 + b = 140,140$$

$$\sigma^2 = 654,401,400 : 20 - b^2 = 32,700,470, \text{ or } \sigma = 5,718.$$

The empirical probability of a birth ( $p_0$ ) is

$p_0 = M : s = 0.02803$ , so that  $q_0 = 1 - p_0 = 0.97197$  and the Bernoullian dispersion

$$\sigma_B = \sqrt{sp_0 q_0} = 369.0.$$

The actual observed dispersion (5,718) is thus much greater than the Bernoullian. The birth series is considerably hyper-normal. The Lexian ratio has the value

$$L = 5,718 : 369.0 = 15.50,$$

while the Charlier coefficient of disturbancy is:

$$100\rho = 4.07.$$

Both the values of  $L$  and  $\rho$  show that the birth series by no means can be compared with the ordinary games of chance but is subject to outward perturbing influences.

**86. Child Births in Denmark.**—The following example shows the corresponding birth series for Denmark in the 25-year period from 1888–1912 as reduced to a stationary population of 2,500,000. The computation of the various parameters follows:

$$b = (39,713 - 30,287) : 25 = + 377,$$

$$M = M_0 + b = 73,377,$$

$$\sigma^2 = 281,208,156 : 25 - b^2 = 11,106,197.2,$$

$$\sigma_B^2 = sp_0 q_0 = 71,223. \quad (p_0 = M : s = 0.0293508),$$

$$L = \sigma : \sigma_B = 12.5$$

$$100\rho = 100(\sqrt{\sigma^2 - \sigma_B^2}) : M = 4.52.$$

NUMBER OF CHILDREN BORN IN DENMARK AS TO CALENDAR YEAR.

$s = 2,500,000$ ,  $N = 25$ ,  $M_0 = 73,000$ .

| Year. | m.     | m - M <sub>0</sub> | (m - M <sub>0</sub> ) <sup>2</sup> |
|-------|--------|--------------------|------------------------------------|
| 1888  | 78,659 | + 5,659            | 32,024,281                         |
| 89    | 77,956 | + 4,956            | 24,561,936                         |
| 1890  | 76,154 | + 3,154            | 9,947,716                          |
| 91    | 77,377 | + 4,377            | 19,158,129                         |
| 92    | 74,059 | + 1,059            | 1,121,481                          |
| 93    | 76,965 | + 3,965            | 15,721,225                         |
| 94    | 75,956 | + 2,956            | 8,740,636                          |
| 1895  | 75,649 | + 2,649            | 7,017,201                          |
| 96    | 76,183 | + 3,183            | 10,131,489                         |
| 97    | 74,404 | + 1,404            | 1,971,216                          |

| Year.                   | m.     | m-M <sub>0</sub> . | (m-M <sub>0</sub> ) <sup>2</sup> . |
|-------------------------|--------|--------------------|------------------------------------|
| 98                      | 75,570 | + 2,570            | 6,604,900                          |
| 99                      | 74,236 | + 1,236            | 1,527,606                          |
| 1900                    | 74,146 | + 1,146            | 1,313,316                          |
| 01                      | 74,341 | + 1,341            | 1,798,281                          |
| 02                      | 73,058 | + 58               | 3,364                              |
| 03                      | 71,802 | - 1,198            | 1,435,204                          |
| 04                      | 72,359 | - 641              | 410,881                            |
| 1905                    | 70,981 | - 2,019            | 4,076,361                          |
| 06                      | 71,280 | - 1,720            | 2,958,400                          |
| 07                      | 70,516 | - 2,484            | 6,170,256                          |
| 08                      | 71,438 | - 1,567            | 2,455,489                          |
| 09                      | 79,597 | - 2,403            | 5,774,409                          |
| 1910                    | 68,777 | - 4,223            | 17,833,729                         |
| 11                      | 66,016 | - 6,984            | 48,776,256                         |
| 1912                    | 65,952 | - 7,048            | 49,674,304                         |
| Sum: $\Sigma$ = -30,287 |        | +39,713            | 281,208,156                        |

Practically the same deductions hold true for this Danish series as for the Swedish series. We meet again a hypernormal series subject to perturbing influences. The closeness of the two values of the Charlier coefficient of disturbancy indicates that the number of births in Sweden and Denmark apparently are subject to the same outward disturbing influences.

**87. Danish Marriage Series.**—The following table shows the number of marriages in Denmark from 1888–1912.

NUMBER OF MARRIAGES IN DENMARK.

$s = 2,500,000$ ,  $N = 25$ ,  $M_0 = 18,000$ .

| Year. | m.     | m-M <sub>0</sub> . | (m-M <sub>0</sub> ) <sup>2</sup> . |
|-------|--------|--------------------|------------------------------------|
| 1888  | 17,605 | - 395              | 156,025                            |
| 89    | 17,622 | - 378              | 142,884                            |
| 1890  | 17,181 | - 819              | 670,761                            |
| 91    | 17,017 | - 983              | 966,289                            |
| 92    | 17,012 | - 988              | 976,144                            |
| 93    | 17,676 | - 324              | 104,976                            |
| 94    | 17,445 | - 555              | 308,025                            |
| 1895  | 17,736 | - 264              | 69,696                             |
| 96    | 18,239 | + 239              | 57,121                             |
| 97    | 18,676 | + 676              | 456,976                            |
| 98    | 18,870 | + 870              | 756,900                            |
| 99    | 18,661 | + 661              | 436,921                            |
| 1900  | 19,015 | +1,015             | 1,030,225                          |
| 01    | 17,870 | - 130              | 16,900                             |
| 02    | 17,712 | - 288              | 82,944                             |
| 03    | 17,791 | - 209              | 43,681                             |
| 04    | 17,895 | - 105              | 11,025                             |
| 1905  | 17,947 | - 53               | 2,809                              |

| Year.                  | m.     | m-M <sub>0</sub> . | (m-M <sub>0</sub> ) <sup>2</sup> . |
|------------------------|--------|--------------------|------------------------------------|
| 06                     | 18,592 | + 592              | 350,464                            |
| 07                     | 19,072 | +1,072             | 1,149,184                          |
| 08                     | 18,750 | + 750              | 562,500                            |
| 09                     | 18,453 | + 453              | 205,209                            |
| 1910                   | 18,255 | + 255              | 65,025                             |
| 11                     | 17,749 | - 251              | 63,001                             |
| 1912                   | 18,034 | + 34               | 1,156                              |
| <hr/>                  |        |                    |                                    |
| Sum: $\Sigma$ = -5,742 |        | +6,617             | 8,686,841                          |

Hence we have:

$$b = (6,617 - 5,742) : 25 = 35, \quad M = M_0 + b = 18,035.$$

$$\sigma^2 = (8,686,841 : 25) - b^2 = 346,249, \quad \sigma = 588.43,$$

$$\sigma_B = 133.81, \quad L = 4.41, \quad 100\rho = 5.73.$$

We encounter again a hypernormal series with quite large perturbations. For Sweden Charlier has computed the coefficient of disturbancy for marriages in the period 1876-1900 and found it to be 5.49. A comparison with the same quantity for the above Danish data shows that the perturbing influences for the two countries are about the same.

88. Stillbirths.—As another example from vital statistics I give the number of stillbirths in Denmark from 1888-1912 as compared with a hypothetical number of 70,000 births per annum.

NUMBER OF STILLBIRTHS IN DENMARK AS REDUCED TO A STATIONARY NUMBER OF 70,000 BIRTHS PER ANNUM.

$$s = 70,000, \quad N = 25, \quad M_0 = 1,700.$$

| Year. | m.    | m-M <sub>0</sub> . | (m-M <sub>0</sub> ) <sup>2</sup> . |
|-------|-------|--------------------|------------------------------------|
| 1888  | 1,861 | + 161              | 25,921                             |
| 89    | 1,924 | + 224              | 50,176                             |
| 1890  | 1,830 | + 130              | 16,900                             |
| 91    | 1,779 | + 79               | 6,241                              |
| 92    | 1,811 | + 111              | 12,321                             |
| 93    | 1,788 | + 88               | 7,744                              |
| 94    | 1,719 | + 19               | 361                                |
| 1895  | 1,753 | + 53               | 2,809                              |
| 96    | 1,714 | + 14               | 196                                |
| 97    | 1,811 | + 111              | 12,321                             |
| 98    | 1,797 | + 97               | 9,409                              |
| 99    | 1,737 | + 37               | 1,369                              |
| 1900  | 1,696 | - 4                | 16                                 |
| 01    | 1,732 | + 32               | 1,024                              |
| 02    | 1,694 | - 6                | 36                                 |
| 03    | 1,685 | - 15               | 225                                |
| 04    | 1,682 | - 18               | 324                                |

| Year.                                           | m.    | $M - m_0$ | $(m - M_0)^2$ |
|-------------------------------------------------|-------|-----------|---------------|
| 1905                                            | 1,705 | + 5       | 25            |
| 06                                              | 1,620 | - 80      | 6,400         |
| 07                                              | 1,723 | + 23      | 529           |
| 08                                              | 1,694 | - 6       | 36            |
| 09                                              | 1,665 | - 35      | 1,225         |
| 1910                                            | 1,658 | - 42      | 1,764         |
| 11                                              | 1,659 | - 42      | 1,764         |
| 12                                              | 1,638 | - 62      | 3,844         |
| Sum: $\Sigma = -310 \quad +1,184 \quad 161,216$ |       |           |               |

Actual computation gives:

$$b = (1,184 - 310) : 25 = 34.96, \quad M = 1,734.96,$$

$$\sigma^2 = 161,216 : 25 - b^2 = 5,226.44, \quad 100\rho = 3.407.$$

The series is again hypernormal. We shall show presently, when discussing the disturbing influences, that this series after the elimination of the secular perturbations actually represents a normal series. In the meantime we give a few examples relating to accident statistics.

89. Coal Mine Fatalities.—The following table gives the number of deaths from accidents in coal mines in various countries in the period 1901–1910 together with the number of comparison  $s$ .

| Year | Belgium<br>$s = 140,000$ | Austria<br>$s = 68,000$ | England<br>$s = 900,000$ | France<br>$s = 180,000$ | Germany<br>$s = 500,000$ | Japan<br>$s = 110,000$ | United States<br>$s = 610,000$ |
|------|--------------------------|-------------------------|--------------------------|-------------------------|--------------------------|------------------------|--------------------------------|
| 1901 | 164                      | 81                      | 1,224                    | 218                     | 1,170                    | 263                    | 1,982                          |
| 02   | 150                      | 73                      | 1,116                    | 196                     | 995                      | 188                    | 2,263                          |
| 03   | 160                      | 50                      | 1,134                    | 184                     | 960                      | 278                    | 1,952                          |
| 04   | 130                      | 62                      | 1,116                    | 193                     | 900                      | 239                    | 2,135                          |
| 1905 | 127                      | 99                      | 1,215                    | 187                     | 930                      | 354                    | 2,214                          |
| 06   | 133                      | 70                      | 1,161                    | 1,262                   | 985                      | 578                    | 2,944                          |
| 07   | 144                      | 73                      | 1,179                    | 198                     | 1,240                    | 399                    | 2,977                          |
| 08   | 150                      | 58                      | 1,188                    | 171                     | 1,355                    | 262                    | 2,220                          |
| 09   | 133                      | 73                      | 1,287                    | 210                     | 1,021                    | 667                    | 2,440                          |
| 1910 | 133                      | 63                      | 1,530                    | 194                     | 985                      | 245                    | 2,391                          |

This gives the following values for the Charlier coefficient:

|          | $100\rho$          |
|----------|--------------------|
| Belgium  | 2.55               |
| Austria  | 13.85              |
| England  | 4.71               |
| France   | 34.19              |
| Germany  | 9.27               |
| Japan    | 44.12 <sup>1</sup> |
| U. S. A. | 12.07              |

<sup>1</sup> I doubt whether the Japanese data as given by the Bureau of Mines are reliable.

The comparatively large values of  $\rho$  show that the fatal accidents in coal mines are subject to violent perturbations. The disturbing influences are greatest for France where the Charlier coefficient is above 34, which immediately shows that some powerful disturbing influence has made itself felt. Looking over the table we find a very large number of deaths for the year 1906. The extremely heavy death rate in this year was caused by the Courrieres mine explosion, in which 1,099 persons lost their lives and marks probably the most fatal disaster in the whole history of coal-mining. Eliminating this catastrophe from the data in the table given above we find indeed that the coefficient of disturbancy becomes imaginary, indicating very stable conditions in French mines. Thus eliminating the more fatal catastrophes we get at least for France a subnormal series for the everyday accidents. In order better to illustrate the influence of the elimination of the most disturbing catastrophes I submit the following two series as reduced to a stationary  $s = 630,000$  of fatal coal mine accidents in the United States in the period 1900-1914 as recorded by the Bureau of Mines. The first series shows total number of deaths  $m_k$ , the second series gives the total deaths  $m_k'$  per year after eliminating all such accidents in which 5 or more men were killed.

NUMBER OF DEATHS FROM ACCIDENTS IN COAL MINES IN UNITED STATES.  
 $s = 630,000$ ,  $N = 15$ .

|      | $m_k$ | $m_k'$ |      | $m_k$ | $m_k'$ |
|------|-------|--------|------|-------|--------|
| 1900 | 2,173 | 1,843  | 1908 | 2,293 | 1,967  |
| 01   | 2,048 | 1,863  | 09   | 2,520 | 2,053  |
| 02   | 2,337 | 1,837  | 1910 | 2,470 | 2,085  |
| 03   | 2,016 | 1,768  | 11   | 2,350 | 1,984  |
| 04   | 2,205 | 1,911  | 12   | 2,060 | 1,839  |
| 1905 | 2,286 | 1,964  | 13   | 2,350 | 1,957  |
| 06   | 2,111 | 2,075  | 1914 | 2,070 | 1,810  |
| 07   | 3,074 | 2,190  |      |       |        |

The first series gives a coefficient of disturbancy equal to 11.06 while the same quantity for the second series has the value 5.51. Despite the fact that the coefficient of disturbancy is reduced about 50 per cent. there still remains disturbing influences, which clearly shows that conditions in American mines are not so stable as in the mines of France, Belgium and England.

90. **Reduced and Weighted Series in Statistics.**—So far all our problems in statistical analysis have been related to series where the value of  $s$  was constant or where the ratio  $s : s_k$  was so close to unity that it might be used as a factor of proportionality. We shall now consider the case where this ratio differs greatly from unity. As an illustration of this kind of series I choose the number of fatal coal mine accidents in various states of the American Federation together with the number of people engaged in coal mining in these states. The figures as taken from the report of the Bureau of Mines relate to the year of 1914.<sup>1</sup>

NUMBER OF PERSONS ENGAGED IN MINING ( $s_k$ ) AND NUMBER KILLED ( $m_k$ ) IN 20 STATES DURING THE YEAR 1914.

|                      | $s_k$ . | $m_k$ . | $ps_k$ . | $ m_k - ps_k $ .       |
|----------------------|---------|---------|----------|------------------------|
| 1 Alabama.....       | 24,552  | 128     | 73       | 55                     |
| 2 Colorado.....      | 10,550  | 75      | 31       | 44                     |
| 3 Illinois.....      | 79,529  | 141     | 237      | 96                     |
| 4 Indiana.....       | 22,110  | 44      | 66       | 22                     |
| 5 Iowa.....          | 15,757  | 37      | 47       | 10                     |
| 6 Kansas.....        | 12,500  | 33      | 37       | 4                      |
| 7 Kentucky.....      | 26,332  | 61      | 79       | 18                     |
| 8 Maryland.....      | 5,675   | 18      | 17       | 1                      |
| 9 Missouri.....      | 10,418  | 19      | 31       | 12                     |
| 10 New Mexico.....   | 4,021   | 18      | 12       | 6                      |
| 11 Ohio.....         | 45,815  | 62      | 136      | 74                     |
| 12 Oklahoma.....     | 8,948   | 31      | 27       | 24                     |
| 13 Pennsylvania..... | 175,745 | 595     | 524      | 71 (Anthracite Mines)  |
| 14 Pennsylvania..... | 172,196 | 402     | 513      | 111 (Bituminous Mines) |
| 15 Tennessee.....    | 9,580   | 26      | 29       | 3                      |
| 16 Texas.....        | 4,900   | 11      | 15       | 4                      |
| 17 Virginia.....     | 9,162   | 27      | 27       | 0                      |
| 18 Washington.....   | 5,730   | 17      | 17       | 0                      |
| 19 W. Virginia.....  | 74,786  | 371     | 223      | 148                    |
| 20 Wyoming.....      | 8,353   | 51      | 25       | 26                     |
| Sum: $\Sigma$ =      | 726,659 | 2,167   | 709      |                        |

It will be noted that the population engaged in mining varies greatly from state to state. In making a simple reduction to a common number of comparisons by a proportional factor it is evident, however, that we would give the same weight to the observed from New Mexico with a population of miners equal to

<sup>1</sup> Catastrophes in the Eccles Mine in West Virginia and in the Royalton Mine of Illinois are eliminated.

4,021 as to the mining population of the state of Pennsylvania where over 340,000 persons are engaged in the same industry. This procedure is faulty. Let us imagine for the moment two sets of drawings from a bag containing white and black balls. The first sample set contained 10,000 drawings and the second set only 100 drawings. If these series were reduced to a common number of comparison  $s = 1,000$  we should have

$\frac{1,000}{10,000} m_1$  and  $\frac{1,000}{100} m_2$  ( $m_1$  and  $m_2$  standing for the number of white balls) as the number of white balls drawn in sample sets of 1,000 single drawings.

But these values are not equally reliable. The mean error in the second series is in fact 10 times as large as the mean error in the first series. In order to overcome this difficulty we ask the reader to consider the following series:

The element  $\frac{s}{s_1} m_1$  is repeated  $s_1$  times

|   |   |                     |   |   |       |   |
|---|---|---------------------|---|---|-------|---|
| “ | “ | $\frac{s}{s_1} m_1$ | “ | “ | $s_1$ | “ |
| “ | “ | $\frac{s}{s_2} m_2$ | “ | “ | $s_2$ | “ |
| “ | “ | $\frac{s}{s_3} m_3$ | “ | “ | $s_3$ | “ |
| . | . | .                   | . | . | .     | . |
| . | . | .                   | . | . | .     | . |
| “ | “ | $\frac{s}{s_N} m_N$ | “ | “ | $s_N$ | “ |

In this way we obtain a series with  $s_1 + s_2 + s_3 + \dots + s_N$  elements which may be termed a *reduced and weighted series* since the larger  $s_k$  appears oftener than the smaller values of  $s_k$ . We shall now see if it is possible to determine the expected value of the mean and the dispersion if the series is supposed to follow the Bernoullian Law.

The mean is defined by the following relation:

$$M = \left[ \overbrace{\frac{s}{s_1} m_1 + \dots + \frac{s}{s_1} m_1}^{s_1} + \overbrace{\frac{s}{s_2} m_2 + \dots + \frac{s}{s_2} m_2}^{s_2} \right]$$

$$\begin{aligned}
 & + \cdots + \overbrace{\frac{s}{s_N} m_N + \cdots + \frac{s}{s_N} m_N}^{s_N} \Big] \div [s_1 + s_2 + \cdots + s_N] \\
 & = \frac{\sum s_k \frac{s}{s_k} m_k}{\sum s_k} = \frac{s \sum m_k}{\sum s_k}.
 \end{aligned}$$

Denoting the average empirical probability by  $p_0$  we have  $\sum m_k : \sum s_k = p_0$  and,

$$M_B = s p_0.$$

As to the dispersion it takes on the following form:

$$\begin{aligned}
 \sigma^2 &= \left[ \overbrace{\left( \frac{s}{s_1} m_1 - s p_0 \right)^2}^{s_1} + \cdots + \left( \frac{s}{s_1} m_1 - s p_0 \right)^2 \right. \\
 & \quad + \overbrace{\left( \frac{s}{s_2} m_2 - s p_0 \right)^2}^{s_2} + \cdots + \left( \frac{s}{s_2} m_2 - s p_0 \right)^2 + \cdots \\
 & \quad \left. + \overbrace{\left( \frac{s}{s_N} m_N - s p_0 \right)^2}^{s_N} + \cdots + \left( \frac{s}{s_N} m_N - s p_0 \right)^2 \right] \\
 & \quad \div [s_1 + s_2 + \cdots + s_N] \\
 &= \frac{\left( \sum s_k \frac{s}{s_k} m_k - s p_0 \right)^2}{\sum s_k} = \frac{\sum \frac{s^2}{s_k} (m_k - s_k p_0)^2}{\sum s_k} \quad (k = 1, 2, 3, \dots N).
 \end{aligned}$$

In finding the theoretical dispersion, assuming a Bernoullian distribution for which  $p_0$  may be used as an approximation of the mathematical a priori probability, we ask the reader to examine the general term of the expression for  $\sigma^2$ , viz.:

$$\left[ \frac{s^2}{s_k} (m_k - s_k p_0)^2 \right] : \sum s_k.$$

If the individual trials follow the Bernoullian Law the expected value of the factor  $(m_k - s_k p_0)^2$  takes the form:

$$e[(m_k - s_k p_0)^2] = \sum (m_k - s_k p_0)^2 \varphi(m_k) = s_k p_0 q_0.$$

This brings the general term for  $\sigma^2$  to the form:

$$\frac{s^2}{\sum s_k} p_0 q_0 = \frac{s}{\sum s_k} s p_0 q_0.$$

Thus the expected value of  $\sigma^2$  according to the Bernoullian distribution may be written as follows:

$$\sigma_B^2 = \sum_{k=1}^{h=N} \frac{s}{\Sigma s_k} s p_0 q_0 = \frac{N s}{\Sigma s_k} s p_0 q_0, \text{ or } : \sigma_B = f \sqrt{N s p_0 q_0},$$

where as before  $p_0 = \Sigma m_k : \Sigma s_k$  and  $f = \sqrt{\frac{N s}{\Sigma s_k}}$ .

These formulas give us the means of computing the Lexian Ratio and the Charlier coefficient of disturbancy in the ordinary way. Some of the computations require, however, a great amount of arithmetical work and the goal is reached more easily by making use of the mean deviation (in § 74a). We found there the following relation:

$$\sigma = 1.2533 \vartheta.$$

In the weighted series it is readily seen that the value of  $\vartheta$  will be of the form:

$$\frac{\Sigma s_k \left| \frac{s}{s_k} m_k - s p_0 \right|}{\Sigma s_k} = \frac{\Sigma s |m_k - s_k p_0|}{\Sigma s_k}.$$

If the series may be assumed to follow a Bernoullian distribution we have

$$\sigma_B = 1.2533 \vartheta.$$

From the above formulas it is readily noticed that we may find the mean and the dispersion directly from the observed series without a preliminary reduction to a common number of comparison  $s$ . This is in fact the method used in the above example of coal-mine accidents in various states. We have:

$$\begin{aligned} p_0 &= \Sigma m_k : \Sigma s_k = 2,167 : 726,659 = .002982, \\ \vartheta &= \frac{\Sigma s |m_k - s_k p_0|}{\Sigma s_k} = 1,000 \times 709 : 726,659 = 0.9757, \\ \sigma &= 1.2533 \times \vartheta = 1.223, \\ \sigma_B^2 &= f^2 s p_0 q_0 = \frac{20,000}{726,659} \times 1,000 \times 0.997 \times 0.003 = 0.0817, \\ 100\rho &= \frac{100 \sqrt{\sigma^2 - \sigma_B^2}}{M} = 40 \text{ approx.} \end{aligned}$$

The large value of the Charlier coefficient of disturbancy clearly shows that conditions in coal mines by no means are uniform in the whole union but vary greatly according to the locality. An actual computation shows in fact that in a few states such as Michigan and Iowa we find an imaginary coefficient of disturbancy whereas States as Ohio and West Virginia exhibit marked hypernormal series with a large coefficient of disturbancy. The establishment of this fact is of some importance in connection with accident assurance. Many statisticians seem to be of the opinion that a standard accident table computed from the data of the whole union ought to serve as the basis for assurance premiums. Such a table would assume uniform conditions all over the union. The enormously high value of  $\rho$  as computed above shows the fallacy of such a view.

**91. Secular and Periodical Fluctuations.**—In the last paragraphs we have just learned how to detect the presence of disturbing influences in a statistical series. A value of the Lexian ratio differing from unity or a value of the Charlier coefficient of disturbancy differing from zero indicates the presence of fluctuations in the chances for the event or phenomena under investigation. After having established the presence of such fluctuations it is the duty of the statistician to trace the sources of the disturbing influences. This is in general done by means of the theory of correlation, which will be discussed in the second volume of this work.

It is, however, possible to classify the disturbances under two categories which by Charlier are termed as *secular* and *periodical* variations.<sup>1</sup> The periodical fluctuations are in general difficult to discuss on account of the variations in the period of the disturbing forces. In many cases we are in absolute ignorance about the length of such a period and therefore unable to subject the series to a mathematical analysis. If the length of the period is known it is indeed not difficult to determine the periodical disturbances. This is often the case in series giving the occurrence of a certain disease in various months. In statistics giving the frequency of malaria in a community the observed cases are

<sup>1</sup> Lexis uses the terms "evolutionary" ("symptomatic") and "periodical" ("oscilating") for such fluctuations.

nearly all limited to the warmer months and infrequent in the winter months.

In the secular fluctuations due to certain outward influences working continually in the same direction it is quite easy to calculate the rate of such variations.

Let  $\beta$  denote the increase (decrease) of the original probabilities ( $p_1, p_2, p_3, \dots p_n$ ) from set to set in the given statistical series so that

$$\begin{aligned} p_2 - p_1 &= \beta \\ p_3 - p_2 &= \beta \\ \cdot &\cdot \cdot \cdot \\ \cdot &\cdot \cdot \cdot \\ p_N - p_{N-1} &= \beta \end{aligned}$$

We then have:

$$p_k = p_1 + (k - 1)\beta. \quad (1)$$

The mean probability has the value:

$$\begin{aligned} p_0 &= \frac{p_1 + p_2 + p_3 + \dots + p_N}{N} \\ &= \frac{p_1 + p_1 + \beta + p_1 + 2\beta + \dots + p_1 + (N - 1)\beta}{N} \quad (2) \\ &= p_1 + \frac{N - 1}{2} \beta. \end{aligned}$$

Eliminating  $p_1$  from (1) and (2) we have:

$$p_k - p_0 = \left( k - \frac{N + 1}{2} \right) \beta.$$

If the observed and reduced numbers  $m_1, m_2, m_3, \dots m_N$  may be regarded as approximately coinciding with  $sp_1, sp_2, sp_3, \dots sp_N$  we may write (2) as follows:

$$m_k - M = \left( k - \frac{N + 1}{2} \right) s\beta \quad (k = 1, 2, 3, \dots N). \quad (3)$$

In order to obtain an expression for  $s\beta$  in known quantities we must eliminate the quantity  $k$ . Multiplying both sides of the equation (3) by  $k - (N + 1)/2$  we have:

$$(m_k - M) \left( k - \frac{N + 1}{2} \right) = \left( k - \frac{N + 1}{2} \right)^2 s\beta.$$

Summing this expression for all values  $k$  from  $k = 1$  to  $k = N$  we have:

$$\Sigma \left( k - \frac{N+1}{2} \right) (m_k - M) = s\beta \Sigma \left( k - \frac{N+1}{2} \right)^2. \quad (4)$$

The following expressions from the summation of series are well known to the reader from elementary algebra:

$$\begin{aligned} \sum_1^N k^2 &= \frac{1}{6} N(N+1)(2N+1), \\ \sum_1^N k &= \frac{1}{2} N(N+1). \end{aligned}$$

Substituting these values in (4) we obtain after a few simple transformations the following expression for  $s\beta$ :

$$s\beta = \frac{12}{N(N^2-1)} \Sigma \left( k - \frac{N+1}{2} \right) (m_k - M). \quad (5)$$

THE SECULAR ANNUAL DECREASE OF NUMBER OF STILLBIRTHS IN DENMARK.  
 $s = 70,000$ ,  $N = 25$ ,  $M = 1,735$

| Year. | $k$ . | $m_k$ . | $m_k - M$ . | $k - \frac{N+1}{2}$ . | $\left( k - \frac{N+1}{2} \right) (m_k - M)$ . |
|-------|-------|---------|-------------|-----------------------|------------------------------------------------|
| 1888  | 1     | 1,861   | +126        | -12                   | - 1,512                                        |
| 89    | 2     | 1,924   | +189        | -11                   | - 2,079                                        |
| 1890  | 3     | 1,830   | +105        | -10                   | - 1,050                                        |
| 91    | 4     | 1,779   | + 44        | - 9                   | - 396                                          |
| 92    | 5     | 1,811   | + 76        | - 8                   | - 808                                          |
| 93    | 6     | 1,788   | + 53        | - 7                   | - 371                                          |
| 94    | 7     | 1,719   | - 16        | - 6                   | + 96                                           |
| 1895  | 8     | 1,753   | + 18        | - 5                   | - 90                                           |
| 96    | 9     | 1,714   | - 21        | - 4                   | + 84                                           |
| 97    | 10    | 1,811   | + 76        | - 3                   | - 228                                          |
| 98    | 11    | 1,797   | + 62        | - 2                   | - 124                                          |
| 99    | 12    | 1,737   | + 2         | - 1                   | - 2                                            |
| 1900  | 13    | 1,696   | - 39        | 0                     | 0                                              |
| 01    | 14    | 1,732   | - 3         | + 1                   | - 3                                            |
| 02    | 15    | 1,694   | - 41        | + 2                   | - 82                                           |
| 03    | 16    | 1,685   | - 50        | + 3                   | - 150                                          |
| 04    | 17    | 1,682   | - 53        | + 4                   | - 212                                          |
| 1905  | 18    | 1,705   | - 30        | + 5                   | - 150                                          |
| 06    | 19    | 1,602   | -115        | + 6                   | - 690                                          |
| 07    | 20    | 1,723   | - 12        | + 7                   | - 84                                           |
| 08    | 21    | 1,694   | - 41        | + 8                   | - 328                                          |
| 09    | 22    | 1,665   | - 70        | + 9                   | - 630                                          |
| 1910  | 23    | 1,658   | - 77        | +10                   | - 770                                          |
| 11    | 24    | 1,658   | - 77        | +11                   | - 847                                          |
| 1912  | 25    | 1,638   | - 97        | +12                   | - 1,164                                        |
|       |       |         |             | Sum:                  | -11,590                                        |

As an example illustrating secular fluctuations I take the previously discussed series of stillbirths in Denmark.

We have in this case

$$\frac{N(N^2 - 1)}{12} = 1,300,$$

hence:

$$s\beta = -11,590 : 1,300 = -8.92.$$

From this we may draw the conclusion that the number of stillbirths in Denmark pr. 70,000 births per annum on the average is decreased by 8.92.

If the fluctuations are of an essential secular character we may write

$$m = M + (k - 13)(-8.92)$$

as the number of stillbirths pr. annum. Apart from accidental fluctuations due to sampling we should therefore obtain a nearly normal series for the 25-year period if we calculated the number of stillbirths each year according to the expression:  $m_k - (k - 13)(-8.92)$ . Such a computation is given below:

NUMBER OF STILLBIRTHS IN DENMARK FREED FROM SECULAR FLUCTUATIONS.  
 $s = 70,000, N = 25.$

| Year. | k. | $m_k - (k - 13)(-8.92).$ | Year. | k. | $m_k - (k - 13)(-8.92).$ |
|-------|----|--------------------------|-------|----|--------------------------|
| 1888  | 1  | 1,754                    | 1900  | 13 | 1,696                    |
| 89    | 2  | 1,826                    | 01    | 14 | 1,741                    |
| 1890  | 3  | 1,741                    | 02    | 15 | 1,712                    |
| 91    | 4  | 1,699                    | 03    | 16 | 1,712                    |
| 92    | 5  | 1,740                    | 04    | 17 | 1,718                    |
| 93    | 6  | 1,726                    | 1905  | 18 | 1,730                    |
| 94    | 7  | 1,666                    | 06    | 19 | 1,675                    |
| 1895  | 8  | 1,708                    | 07    | 20 | 1,875                    |
| 96    | 9  | 1,678                    | 08    | 21 | 1,765                    |
| 97    | 10 | 1,784                    | 09    | 22 | 1,745                    |
| 98    | 11 | 1,779                    | 1910  | 23 | 1,747                    |
| 99    | 12 | 1,728                    | 11    | 24 | 1,756                    |
|       |    |                          | 1912  | 25 | 1,745                    |

A computation of the characteristics of this series gives:

$$M = 1,735, \quad \sigma = 37.09, \quad \sigma_B = 41.6, \quad 100\rho \text{ imaginary.}$$

The dispersion is now slightly subnormal and the coefficient of disturbancy is imaginary whereas in the original series in § 88 it had a value equal to 3.4.

92. Cancer Statistics.—Mr. F. L. Hoffman in his treatise "The Mortality from Cancer Throughout the World" gives some very interesting statistics on mortality from cancer in various localities. Through the kindness of Mr. Hoffman I am able to submit the following series relating to cancer among males in the City of New York (Manhattan and Bronx Boroughs):

DEATHS FROM CANCER ( $m_k$ ) IN THE CITY OF NEW YORK AS REDUCED TO A STATIONARY POPULATION OF 1,000,000.

$$s = 1,000,000, N = 25, M = 560.$$

| Year. | $k$ . | $m_k$ . | $m_k - M$ . | $k - \frac{N+1}{2}$ . | $\left(k - \frac{N+1}{2}\right)(m_k - M)$ . |
|-------|-------|---------|-------------|-----------------------|---------------------------------------------|
| 1889  | 1     | 377     | -183        | -12                   | 2,196                                       |
| 1890  | 2     | 476     | -84         | -11                   | 924                                         |
| 91    | 3     | 410     | -150        | -10                   | 1,500                                       |
| 92    | 4     | 444     | -116        | -9                    | 1,044                                       |
| 93    | 5     | 462     | -98         | -8                    | 784                                         |
| 94    | 6     | 423     | -137        | -7                    | 959                                         |
| 1895  | 7     | 442     | -118        | -6                    | 708                                         |
| 96    | 8     | 493     | -67         | -5                    | 335                                         |
| 97    | 9     | 505     | -55         | -4                    | 220                                         |
| 98    | 10    | 515     | -45         | -3                    | 135                                         |
| 99    | 11    | 513     | -47         | -2                    | 94                                          |
| 1900  | 12    | 547     | -13         | -1                    | 13                                          |
| 01    | 13    | 595     | +35         | 0                     | 0                                           |
| 02    | 14    | 540     | -20         | +1                    | -20                                         |
| 03    | 15    | 580     | +20         | +2                    | 40                                          |
| 04    | 16    | 609     | +49         | +3                    | 147                                         |
| 1905  | 17    | 639     | +79         | +4                    | 316                                         |
| 06    | 18    | 619     | +59         | +5                    | 295                                         |
| 07    | 19    | 658     | +98         | +6                    | 588                                         |
| 08    | 20    | 631     | +71         | +7                    | 497                                         |
| 09    | 21    | 683     | +123        | +8                    | 984                                         |
| 1910  | 22    | 710     | +150        | +9                    | 1,350                                       |
| 11    | 23    | 710     | +150        | +10                   | 1,500                                       |
| 12    | 24    | 721     | +161        | +11                   | 1,771                                       |
| 1913  | 25    | 718     | +158        | +12                   | 1,896                                       |

Sum:  $\Sigma = 18,276$

A computation of the dispersion and the Charlier coefficient of disturbancy gives a value of  $100\rho$  in the neighborhood of 18, indicating marked fluctuations. An inspection of the series shows immediately that there is a marked increase in the rate of death from cancer. Working out the secular disturbances in the ordi-

nary manner we find:

$$s\beta = \frac{18,276}{1,300} = 14.06$$

indicating an increase of death from cancer of about 14 persons pr. annum for a population of 1,000,000. Eliminating the secular disturbances in the same manner as above, we now get a coefficient of disturbancy equal to  $0.983i$  ( $i = \sqrt{-1}$ ), practically a normal dispersion when taking into account the mean error due to sampling.

**93. Application of the Lexian Dispersion Theory in Actuarial Theory. Conclusion.**—The Russian actuary, Jastremsky, has applied the Lexian Dispersion Theory in testing the influence of medical selection in life assurance.<sup>1</sup> The research by Jastremsky evolves about the following question. Is medical selection a phenomena independent of the age of the assured? Let  ${}^{(t)}q_x$  denote the observed rate of mortality after  $t$  years' duration of assurance. In the same manner  $q_x^{(5)}$  denotes the rate of mortality of a life aged  $x$  after 5 or more years of duration ( $t \leq 5$ ). Forming the ratio  ${}^{(t)}q_x : q_x^{(5)}$  for all ages of  $x$  we obtain a certain homograde series for which we may compute the Lexian Ratio and the Charlier Coefficient and thus determine if the fluctuations are due to sampling only or dependent on the age of the assured. Space does not allow us to give a detailed account of the very interesting research by Jastremsky as applied to the Austro-Hungarian Mortality Table (Vienna, 1909), and we shall limit ourselves to quote his final results as to the Lexian Ratio,  $L$ , for Whole Life Assurances and Endowment Assurances:

|     | Whole Life Assurances. | Endowment Assurances |
|-----|------------------------|----------------------|
| $t$ | $L$                    | $L$                  |
| 1   | 0.88                   | 1.01                 |
| 2   | 0.89                   | 0.96                 |
| 3   | 1.12                   | 1.05                 |
| 4   | 1.05                   | 0.98                 |
| 5   | 1.07                   | 0.91                 |

The above values of  $L$  all lie close to unity and the series may therefore be considered as a Bernoullian Series where the fluctu-

<sup>1</sup> Jastremsky: "Der Auslese-Koeffizient," *Zeitschr. f. d. ges. Vers.-Wiss.*, Band XII, 1912.

ations are due to sampling entirely. Or in other words, the ratio  $\varphi_t = {}^{(1)}q_x : q_x^{(6)}$  is a quantity independent of the age of the assured.

The great majority of statistical series may be subjected to a similar analysis as given in the preceding chapters. The characteristics as described previously, the Lexian Ratio and the coefficient of disturbancy, tell us the magnitude of possible fluctuations from sample to sample. In many cases we may by means of the secular coefficient of disturbancy,  $\beta$ , partly or wholly eliminate such fluctuations, due to secular causes, and thus be in a better position to study the periodical fluctuations.

A statistical research may be likened to the navigation of a difficult waterway, full of hidden rocks and skerries out of sight to the navigator. The amateur statistician, sailing the ocean in a blind and happy-go-lucky manner, often comes to grief on those rocks and suffers a total shipwreck. The skillful navigator, the mathematically trained statistician, is always on the lookout for the sea marks. In the Lexian Ratio and the Charlier Coefficient of Disturbancy he recognizes a beacon light, often signaling "Danger ahead." He stops his engines. In case he does not possess the particular charts giving the exact location of the hidden reefs his prudence advises him to call a pilot to bring his ship safely in harbor. On the other hand, if he has reliable charts and knows his profession thoroughly he may venture forth and do his own piloting, by a study of the charts. It is to the study of such charts—*i. e.*, a special study of the higher statistical characteristics—that we shall turn our attention in the second part of this treatise. The reader who has followed us up to this point may perhaps feel discouraged by realizing how little he has gained in knowledge after having learned a mass of technical detail and formulas. We can quite appreciate and understand this feeling. So far, he has perhaps chiefly been impressed by the treacherous and misleading character of statistical mass phenomena, but to recognize a danger signal and thus avoid the pitfalls is one of the fundamental essentials in safe navigation in statistical research.

## ADDENDA.

### APPENDIX AND BIBLIOGRAPHICAL NOTES.

#### CHAPTER I.

Page 3. The establishment of the relations between hypothetical judgments and probabilities is probably first due to F. C. LANGE. See also the discussion in SIGWART's "Logic" (English translation, Macmillan Co., New York, 1904). A defense of the "principle of insufficient reason" as opposed to the view of von Kries is given by K. STUMPF ("Über den Begriff der mathematischen Wahrscheinlichkeit") *Ber. bayr. Ak. (phil. Kl.)*, 1892. For a further discussion of the philosophical aspect the reader is advised to consult "Theorie und Methoden der Statistik" (Tubingen, 1913) by the Russian statistician, A. KAUFMANN.

#### CHAPTER II.

Page 21. An interesting account of the application of the theory of probabilities to whist is given by POOLE in "Philosophy of Whist Play" (New York and London, 1883). Page 23. Example 6. This is a general case of the so-called game of "Treize" or "Recontre" first discussed by MONTMORT in his "Essai sur les Jeux des Hazards" (1708). "Thirteen cards numbered 1, 2, 3, . . . up to 13 are thrown promiscuously into a bag and then drawn out singly; required the chance that once at least the number on a card shall coincide with the number expressing the order in which it is drawn." This is one of the stock problems in probability and has been discussed by nearly all the leading classical writers on the subject.

#### CHAPTER IV.

The close connection between probability and symbolic logic is admirably discussed by the Italian mathematician, PEANO, in various of his mathematical texts. Page 42. Example 19. See also the discussion by R. HENDERSON in "Mortality and Statistics" (New York, 1915).

#### CHAPTER V.

38. The moral expectation has been discussed by HARALD WESTERGAARD in "Tidskrift for Matematik" (1878) and in "Smaaskrifter tilegnede C. F. Krieger" (Copenhagen, 1889).

#### CHAPTER VI.

A German translation with explanatory notes of BATES's brochure has recently appeared in the series of "Ostwald's Klassiker."

Page 74. The double integral in the numerator of (IV) is evidently of the form:

$$\iint_{(A)} F(y_1, y_2) dy_1 dy_2,$$

where the contour of the field of integration ( $A$ ) is defined by means of the relations:

$$\alpha < y_1 y_2 < \beta, \quad 0 < y_1 < 1 \quad \text{and} \quad 0 < y_2 < 1.$$

The field of integration is thus the area swept out by the hyperbola  $y_1 y_2 = \alpha$ , the straight line  $y_2 = 1$ , the hyperbola  $y_1 y_2 = \beta$  and the straight line  $y_1 = 1$ .

Changing the variables by means of the transformation:

$$y_1 y_2 = y = \varphi(y, z) \quad \text{and} \quad 1 - y_1 = z(1 - y) = \psi(y, z)$$

we get the following new double integral

$$\iint_{(A_1)} F[\varphi(y, z), \psi(y, z)] |J| dy dz \quad (|J| \text{ taken as absolute value}),$$

where  $J$  is the Jacobian or functional determinant defined by the formula:

$$J = \begin{vmatrix} \frac{\partial \varphi}{\partial y} & \frac{\partial \varphi}{\partial z} \\ \frac{\partial \psi}{\partial y} & \frac{\partial \psi}{\partial z} \end{vmatrix} = \frac{\partial \varphi}{\partial y} \frac{\partial \psi}{\partial z} - \frac{\partial \varphi}{\partial z} \frac{\partial \psi}{\partial y}.$$

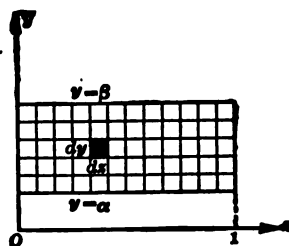
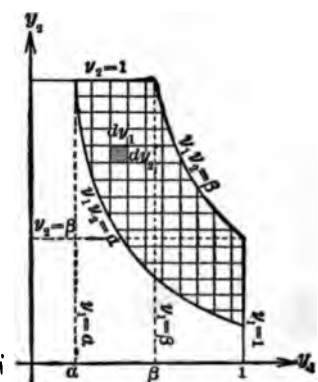
For

$$y_2 = \frac{y}{1 - z(1 - y)} = \varphi(y, z),$$

$$y_1 = 1 - z(1 - y) = \psi(y, z),$$

$$|J| = \left\| \begin{array}{cc} 1 - z & y(1 - y) \\ \frac{1 - z}{z} & - (1 - y) \end{array} \right\| = \frac{1 - y}{1 - z(1 - y)}$$

The transformation in a double integral implies in general three parts (1) the expression of  $F(y_1 y_2)$  in terms of  $y, z$  (2) the determination of the new system of limits (3) substitution of  $dy_1 dy_2$ . The solution of the third part we just gave above. The solution of the two first is purely algebraically. The first part is a straightforward simple problem which should present no difficulty



<sup>1</sup> See GOURSAT: "Mathematical Analysis" (New York, 1904) pages 266-67.

whatsoever to the student and which in conjunction with (3) brings the integrands on the form given in formula (V).

The easiest way to determine the new system of limits is probably by constructing the contour in the new field of integration. The hyperbolas  $y_1 y_2 = \alpha$  and  $y_1 y_2 = \beta$  are in the new field of integration changed into the two straight lines  $y = \alpha$  and  $y = \beta$  which determine the limits for the variable  $y$ . A mere inspection of the expressions for  $\varphi(y, z)$  and  $\psi(y, z)$  shows that the two straight lines  $y_2 = 1$  and  $y_1 = 1$  become in the new field  $z = 1$  and  $z = 0$  which are the limits for  $z$ .

The contour (A<sub>1</sub>) simply becomes a rectangle bounded by the straight lines  $z = 0$ ,  $y = \beta$ ,  $z = 1$  and  $y = \alpha$ . The complete transformation finally brings the numerator on the form as given in (V).

Page 75. The question put by Mr. Bing is simply the determination of a future event by means of Bayes's Rule. The limits  $\alpha$  and  $\beta$  become 0 and 1 respectively and the contour of the field of integration simply becomes the area bounded by  $y_1 y_2 = 0$ ,  $y_2 = 1$ ,  $y_1 y_2 = 1$  and  $y_1 = 1$ , i. e., the area enclosed between the two axis, the line  $y_2 = 1$ , the hyperbola  $y_1 y_2 = 1$  and the line  $y_1 = 1$ . The transformed contour becomes a square with side equal to unity.

## CHAPTER VII.

Page 83. The criticism by the English empiricists is to a certain extent due to a misconception of the Bernoullian Theorem. "This theorem," VENN says, "is generally expressed somewhat as follows: That in the long run all events will tend to occur with a frequency proportional to their objective probabilities." Any one giving careful attention to the deduction of the famous theorem will, however, readily notice the fallacy of such a view. Not the actual absolute frequencies of the events but the *mathematical expectations of such events* are proportional to the a priori mathematical probability  $p$ . The fallacy of Mr. Venn lies in his confusing an actual event with its mathematical expectation. In other words, he makes the Bernoullian Theorem appear as a regular hypothetical judgment whereas as a matter of fact it is a simple probability judgment. If one is to take such an erroneous view of the Bernoullian Theorem one may even be reconciled with another startling statement by Venn that "If the chance (against the happening of a certain event) be 1,023 to 1 it undoubtedly will happen once in 1,024 trials."

For a clear presentment of the empirical methods and their relation to mathematical probabilities and deductive methods see v. BORTKIEWICZ "Kritische Betrachtungen zur theoretischen Statistik" (Jahrb. f. N.-Oe. u. Stat. 3 Folge, Ed. 8, 10, 11) and "Die statistischen Generalisationen" (*Scientia*, Vol. V). v. Bortkiewicz is but one of the brilliant school of Russian statisticians, who has made a thorough study of the philosophical aspects of statistics. The induction method of J. S. MILL is carried much farther and put on a far sounder basis than that originally given by Mill in the brochure "Die Statistik als Wissenschaft" by A. A. TSCHUPROFF as well as in his Russian text "Researches on the Theory of Statistics." The main ideas of the Russian writers are also found in KAUFMANN's "Theorie und Methoden der Statistik" (Tübingen, 1913).

## CHAPTER IX.

Page 95. For a closer approximation of  $n!$  see FORSYTH, A. R., "On an Approximate Expression for  $x!$ " (Brit. Ass. Rep., 1883). Page 107. In this discussion it must be remembered that the variables are independent of each other. The formula:  $e(k\alpha) = ke(\alpha)$  is self evident, but may be proved as follows:

$$e(k\alpha) = ksp = ke(\alpha), \quad e[k\alpha - e(k\alpha)]^2 = k^2e[\alpha - e(\alpha)]^2 = k^2e^2(\alpha), \quad \text{or } e(k\alpha) = ke(\alpha).$$

Page 115. See also a similar discussion by WESTERGAARD in "Mortalit t und Morbilit t" (Jena, 1902), page 187.

## CHAPTER XI.

The still unfinished series of monographs by CHARLIER are found in various volumes of *Meddelande fr n Lunds Astronomiska Observatorium* (Lund, Stockholm) and in *Svenska Aktuari f reningens Tidskrift* (Stockholm).

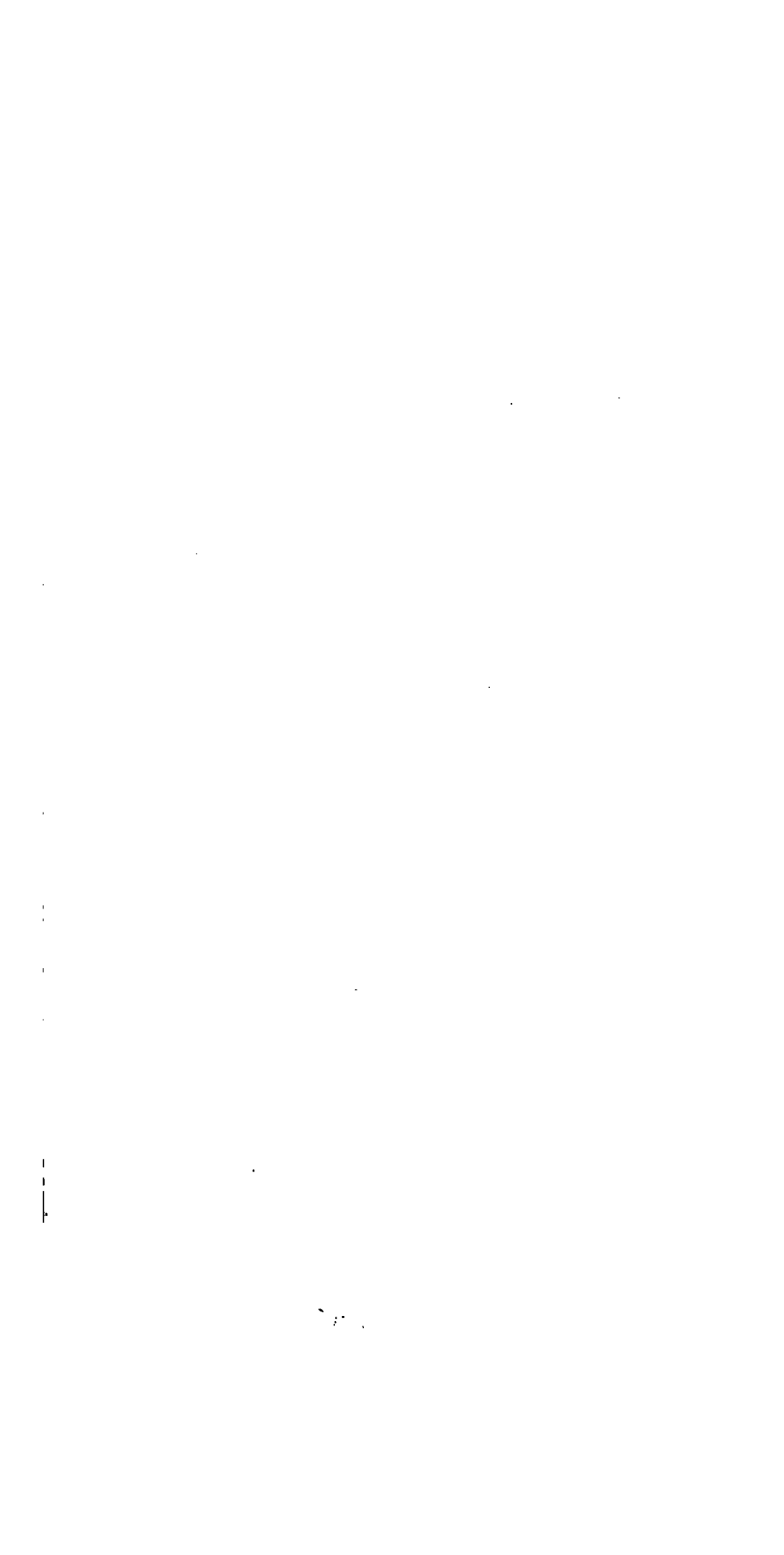
Page 137. Since all statistical characteristics to greater or less extent are effected with mean errors due to sampling it is of importance to be able to determine such mean errors in simple algebraic terms. We shall for the present confine ourselves to the mean and the dispersion. The mean error in the mean,  $M_B$  in a Bernoullian Series is given by the formula:

$$e(M) = \frac{\sqrt{e^2(m_1) + e^2(m_2) + \dots + e^2(m_N)}}{N} = \frac{\sqrt{Nspq_0}}{N} = \frac{\sigma}{\sqrt{N}}.$$

The mean error of the dispersion is somewhat difficult to obtain by elementary methods since it involves the determination of the mean error of the mean error. The mean error square of the mean error square may be gotten by a process similar to that of Laplace in § 65-66 by the introduction of the parameter,  $t$ , in the expression for  $\alpha^2$  and  $\alpha^4$  in  $e[(\alpha - sp)^2 - spq]^2$ . After several reductions this latter expression may be brought to the form:  $2(spq_0)^2 = 2\sigma^2$  (approx.). For the dispersion we have:

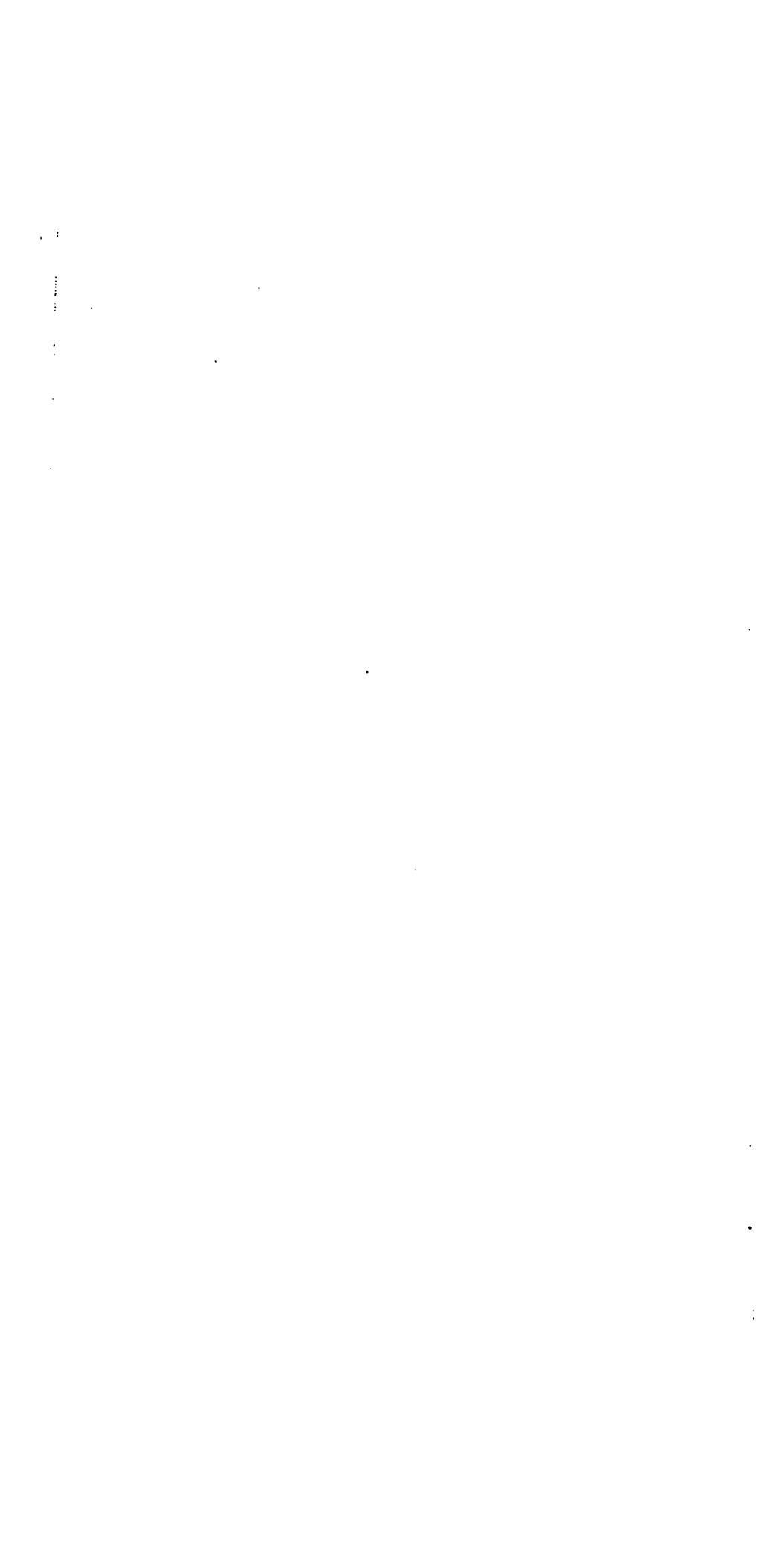
$$e(\sigma) = \frac{\sigma}{\sqrt{2N}}.$$

This formula will be proven under the discussion of frequency curves.









**This book is under no circumstances to be  
taken from the Building**

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